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11   RESEARCH ARTICLE

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13   # **Evaluation of topsoil inversion in UK habitat creation**

14   **and restoration schemes.**

15

16   **Running head**

17   Habitat creation using topsoil inversion.

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30  **Author contributions**

31  EG, EP, SC, JC, LJ, RS conceived and designed the research; RS set up trial sites and contributed

32  materials; EG performed the experiments and analysed the data; EG, EP wrote and edited the

33  manuscript.

# Abstract

35  Habitat creation and restoration schemes on former agricultural soils can be constrained by high

36  residual soil fertility, a weedy seed bank, and a lack of suitable species in the seed rain. Topsoil

37  inversion has been trialled across the UK as a novel technique to address these constraints. We

38  investigated 15 topsoil inversion sites ranging in age (time since inversion) from 6 months to five

39  years. We assessed surface soil fertility compared to adjacent non-inverted soil, and vegetation

40  composition with respect to the species introduced at each site. Soil organic matter, total and

41  extractable N and P were lower in topsoil inversion surface soils, demonstrating that topsoil

42  inversion can successfully reduce surface soil fertility prior to habitat creation and restoration.

43  This reduction was maintained over the timescale of this study (five years). Cornfield annual

44  nurse crops provided instant visual appeal and gave way to grassland species over time. Sown

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45 species varied widely in their establishment success, and sowings were more successful than plug

46 plantings. Grasses colonised naturally following sowing forb-only seed mixes, allowing

47 introduced forbs to establish early on with reduced competition from the seed bank. Plant

48 communities did not yet resemble semi-natural communities, but all were in the early stages of

49 community development. Results indicate that topsoil inversion can successfully lower surface

50 soil fertility and reduce competition between sown species and agricultural weeds.

51

## 52 **Key words**

53 Deep ploughing

54 Nurse crop

55 Seed addition

56 Soil fertility

57 Soil phosphorous

58 Species-rich grassland

59

## 60 **Implications for Practice**

61 • Topsoil inversion is effective in lowering surface fertility of former agricultural soil. This

62 reduction is maintained over a minimum timescale of five years.

63 • Topsoil inversion is effective in reducing competition between sown species and

64 agricultural weeds present in topsoil.

65 • Using a forb-only seed mix allows sown species to establish without competition from

66 grasses, which colonise well naturally. Cornfield annual nurse crops provide early visual

67 appeal and give way to grassland species over time.

68      •   Sown native wildflower species vary widely in their establishment success, with sowings

69         being more effective than plug planting.

70      •   Although topsoil inversion and seed sowing aid the creation of species-rich grassland,

71         there is low resemblance to semi-natural communities in the early stages.

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## 83   Introduction

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85   Semi-natural habitats of high plant diversity are frequently associated with infertile soils (Marrs

86   & Gough 1989). Agricultural soils generally have significantly higher levels of nutrients,

87   particularly extractable P, than semi-natural soils (Marrs et al. 1998), preventing establishment of

88   species characteristic of less fertile soil (Walker et al. 2004). Thus, successful habitat restoration

89   may be more likely when soil nutrient levels are closer to those of target habitats (Critchley et al.

90   2002). Natural community regeneration may also be constrained if species present in the soil seed

91   bank do not match those required in the restored habitat (Hutchings & Booth 1996). Seed bank

92   impoverishment tends to become more pronounced with increasing time since habitat

93   degradation, and with increasing agricultural intensity (Clarke 1997).

94       Traditional methods for lowering soil fertility include grazing, vegetation off-take,

95   burning and topsoil removal (Marrs 1993; Gilbert et al. 2003; Lawson et al. 2004; Jones et al. in

96   press). Topsoil removal aims to cause a rapid simultaneous reduction in surface soil fertility and

97   removal of the soil seed bank in order to achieve successful restoration (Walker et al. 2004).

98   Topsoil inversion has been suggested as a novel alternative technique to topsoil removal (Gilbert

99   et al. 1996; Marrs 2002), although the effects are much less researched. Gilbert et al. (2003)

100  suggest that deep ploughing may be an effective means of reducing P availability in the soil,

101  providing initial concentration decreases with depth. In clay soils where the P enrichment is

102  largely confined to the top 20 cm Gilbert et al. (1996) suggest that topsoil stripping to 20 cm or

103  deep ploughing to 40 cm would be most likely to be successful in reducing surface soil available

104  P. Studies indicate that soil nutrients can be reduced by ploughing more deeply than conventional

105  soil preparation. For example ploughing to 30 cm was found to reduce surface soil total N and

106  extractable K (Allison & Ausden 2004), and to reduce surface soil available P and K (Pywell et

107  al. 2002).

108      Deep ploughing to >50 cm has been used in Scandinavian forestry as a method of

109  improving plantation success. Deep ploughing keeps areas free from vegetation in the first

110  growing season (Matthesen & Damgaard 1997). Pywell et al. (2002) investigated the use of deep

111  cultivation to a depth of 30 to 40 cm in the restoration of species-rich grassland on arable land.

112  Results found that deep cultivation improved restoration success by reducing soil P and K,

113  improving the establishment of sown forbs, and reducing the number of unsown weedy grasses,

114  although the effect weakened after four years. Restored habitat on deep cultivated soil provided

115  the closest match to the target UK National Vegetation Classification (NVC) community

116  (Rodwell 1992) when sown with a species-rich seed mix on a suitable soil type. Other results are

117  less clear. For example Allison and Ausden (2004) found that reduction of soil fertility by deep

118  ploughing was less effective than topsoil removal. In this case, however, the ploughing depth was

119  less than is achievable with the Danish deep plough.

120      In 2002, Landlife set up the first trial site to investigate the use of topsoil inversion in

121  habitat creation, under the project name 'Break New Ground' (Landlife 2008), and was inspired

122  by the use of the deep plough (50-80 cm) in Danish forestry (Pywell et al. 2002; Allison &

123  Ausden 2004). Topsoil inversion results in burial of the topsoil under a layer of subsoil, so that

124  the original layers are intact but their position in the profile is changed. Despite its increasing use

125  by conservation organisations, there are limited published data on the effects of this practice on

126  soil nutrient profiles and plant community establishment. The objectives of this paper were to

127  evaluate the effect of topsoil inversion at 15 trial sites across the UK by evaluating the success

128  and duration of topsoil inversion in altering soil properties, and evaluating the success of sown

129  species and plant community composition and how this relates to soil properties. This will

130  address the requirement for a better understanding of the ecological effects of topsoil inversion in

131  habitat creation and restoration.

132

133  **Methods**

134

135  We selected fifteen topsoil inversion survey sites. Sites selected included a range of ages (time

136  since topsoil inversion) and geographic locations, with a variety of partner organisations and

137  habitat objectives (further details including full names and GPS locations are provided in Table

138  S1). Topsoil inversion had been undertaken using a double-bladed deep plough (Bovlund 64D,

139  Bovlund, Denmark) pulled by a 230 horsepower tractor, detailed in Glen (2009) and Jones et al.

140  (2010). Topsoil inversion results in burial of the surface soil under a layer of subsoil. Depths vary

141  according to soil type but typically will result in approximately 40 cm of topsoil buried under 40

cm of subsoil. We use the term 'topsoil inversion' (TI) to denote sites where this treatment was applied. All but one site was sown with creative conservation seed mixes comprised entirely of forbs. A creative conservation seed mix is one that introduces a mixture of common species as a starting point for community restoration, rather than aiming for a specific target or NVC (National Vegetation Classification) community (Landlife 2008). Additionally, plants at three sites were introduced as plugs. All fourteen sown sites included cornfield annual species to provide a visually appealing nurse crop. Surveys took place in July 2007.

We recorded all plant species present on TI soil, and carried out a quantitative vegetation survey at each site. We placed five x 1 $m^2$ quadrats at random within the inverted area and estimated percentage cover for each species, and percentage bare ground. Total percentage covers were calculated by summing the mean percentage covers for each species.

At each site, we took five surface soil cores at random to a depth of 15 cm from the TI areas, avoiding the outermost 5 m edge. Five soil samples were also taken from the surrounding or adjacent area of soil which had not been inverted, to provide a control. We analysed soil samples separately, giving five replicates each for TI and control surface soils at each site. Soil samples were analysed for pH by adding fresh soil to water at a ratio of 1:2.5 by mass and shaking for 15 minutes (Sykes & Lane 1996). Soil was oven dried at 105°C for 12 hours to calculate gravimetric water content. Nitrate and ammonium were extracted using the KCl extraction method (Allen 1989). Extractable nitrate and ammonium concentrations were then measured using ion exchange chromatography (Dionex (UK) Ltd., Camberley, Surrey) and converted to mg/kg of dry soil. Extractable phosphate was measured using the Olsen (bicarbonate extraction) method (Rowell 1994). Dry soil was homogenised and sieved through 2 mm square mesh sieve. Organic matter was measured by % loss on ignition at 375°C (Ball 1964). Dry soil samples were digested in 2 ml concentrated sulphuric acid at 360°C for 4 hours with 50 mg 100:1 LiCl:Se catalyst (Carroll et al. 2003). Digests were analyzed for concentrations of total N (as

167  ammonium) using ion exchange chromatography (Dionex (UK) Ltd., Camberley, Surrey), and

168  total P using optical emission spectrometry (Inductively Coupled Plasma OES, Varian Inc.,

169  USA).

170      We analysed differences in surface soil characteristics with a paired *t*-test comparing TI

171  surface soil to adjacent surface soil. Organic matter, total N and total P were arcsin transformed

172  prior to analysis, and Olsen P was log transformed, in order to meet the assumption of normality.

173  We used Mann-Whitney tests for extractable nitrate and ammonium data since these were highly

174  right-skewed. Sown species persistence was calculated as percentage of sown species recorded

175  during the survey. We tested for relationships between measures of plant diversity and site

176  variables (age since TI and surface soil measurements) using linear regression analysis or

177  Pearson's correlations. All *t*-tests, Mann-Whitney tests and Pearson's correlations were

178  performed using Minitab (Minitab Statistical Software, Release 14 for Windows, State College,

179  Pennsylvania, USA). For each *t*-test, the number of degrees of freedom was adjusted to account

180  for unequal variances. N values refer to the number of replicates at each data point. Grime's plant

181  strategies were determined from quadrat data using MAVIS (Modular Analysis of Vegetation

182  Information System Plot Analyser v 1.00, Centre for Ecology and Hydrology, UK). Data are

183  presented untransformed.

184

185  **Results**

186

187      **Surface Soil Characteristics**

188  Soil pH was higher in TI than control surface soil for all sites except LU, which had almost

189  identical surface soil pH in TI and control soils. For the remaining sites, eight of these differences

190  were significant (Table 2). This trend occurred regardless of soil pH levels, which varied from pH

191  5.4 to 7.3 in control soils. Although the oldest site (LU) had no pH difference between TI and

192 control soils, and some of the smallest pH differences between TI and control soils were from the

193 oldest sites. There was no significant correlation between the magnitude of the pH difference (TI

194 minus control) and age of site.

195 For 14 sites, surface soil water content was higher in control soil than TI soil, and of

196 these, 11 were significantly different (Table 2). The site with the reverse trend was CH, where TI

197 surface soil was significantly wetter that control surface soil. The magnitude of the difference in

198 surface soil water content between TI and control soils varied greatly, from over 25% difference

199 at PT to just over 3% difference at OP. When all sites were analyzed, there was no significant

200 relationship between the difference in surface soil water content between TI and control, and the

201 age of the site. When the anomalous site was omitted, however, there was a significant negative

202 relationship between age of site and the soil water content difference ($R^2$ = 22.9%, $P$ = 0.048),

203 suggesting a decline in this treatment effect with time.

204 For all sites, surface soil OM was lower in TI soils than controls, with 11 of these

205 differences being significant (Table 2). The magnitude of the difference in surface soil OM

206 between TI and control soils varied considerably, from over 9% difference at PT to 1.8%

207 difference at LU. There was no significant relationship between the difference in surface soil OM

208 between TI and control, and the age of the site.

209 For 14 of the 15 sites, surface soil total N was lower in TI soils than controls, with 12 of

210 these differences being significant (Table 3). The magnitude of the difference in surface soil total

211 N between TI and control soils varied considerably, from around 5 mg/kg difference at PT to 1

212 mg/kg difference at LU. There was no significant relationship between surface soil total N

213 difference between TI and control, and the age of the site.

214 The frequency distribution of all surface soil extractable nitrate levels was highly right-

215 skewed. Surface soil nitrate levels varied between 0.5 mg/kg to over 150 mg/kg in control soils,

216 and between zero to around 19 mg/kg in TI soils. Despite this variation, all 15 sites had higher

217    surface soil nitrate levels in control soils than TI soils (Table 3); this difference was significant

218    for five sites. Surface soil ammonium levels varied between 0.2 and 14.5 mg/kg in control soils,

219    and 0 to 2.5 mg/kg in TI soils. The results for surface soil extractable ammonium levels were

220    similar to that of nitrate, with 13 sites having higher surface soil ammonium levels in control soils

221    than TI soils, five of which were significantly higher.

222         For all 15 sites, surface soil total P was lower in TI soils than controls, with 12 sites being

223    significantly different (Table 3). Data for surface soil Olsen P levels was highly right-skewed.

224    Surface soil Olsen P levels varied from around 7 to > 80 mg/kg in control soils, and from <1 to >

225    35 mg/kg in TI soils. Ten of the 15 sites had a significant difference between surface soil Olsen P

226    in control and TI soils (Table 3). Of these, two sites were significantly higher in TI than control

227    soils (BH and EP), and the remaining eight sites were significantly higher in control soils than TI

228    soils. The sites with significantly higher Olsen P in control soils varied considerably in the

229    magnitude of this difference, with the smallest difference of 5.6 mg/kg at CD, and the largest

230    difference of > 73 mg/kg at FW. All but one of the five sites with no significant difference

231    followed the general trend of having higher Olsen P in control than TI surface soils.

232

233         **Plant Community Establishment**

234    Between 21 and 49 non-woody plant species were recorded at the TI sites. Grasses were present

235    as natural colonisers at all sites, from one to eight species per site. Small numbers of ferns,

236    horsetails and bryophytes were present at some sites. The numbers of species recorded as total,

237    sown, natural colonisers and grasses were not significantly related to the age of the site in months

238    since topsoil inversion. Of all the TI surface soil factors recorded at each site, only extractable

239    nitrate showed a significant relationship with the total number of species ($R^2$ = 20.9, $p$ = 0.049).

240    The number of sown species, natural colonisers and grasses showed no significant relationship

241    with any soil factor.

242    The UK NVC communities determined from the plant species present at each topsoil

243    inversion site included 10 mesotrophic grasslands, three open vegetation communities, one sand

244    dune and one calcifugous grassland community (Table 4). The number of sown species varied

245    from 12 to 28 (Table 5) with the exception of CD which was unsown. The majority of species

246    were introduced as seed; only three sites had plug planting in addition to sowing. None of the

247    species introduced by planting were recorded. Persistence of sown species varied from 20% at

248    BH to 86% at CH (Table 5). There was no relationship between the persistence of sown species

249    and the age of the site in months since topsoil inversion (Figure 1).

250    Twelve of the 15 sites had a nurse crop of five or six species of cornfield annuals (Table

251    S2). The number of cornfield annual species recorded during the survey varied from none to all

252    five or six (Table 5). There was a significant negative relationship between the persistence of

253    sown cornfield annual species and the age of the site in months since topsoil inversion (Figure 1).

254    Sown non-cornfield annual species across all sites numbered 36 species, including

255    biennials and perennials associated with meadow and woodland edge habitats (Table S2). Of

256    these, field scabious *Knautia arvensis*, common knapweed *Centaurea nigra*, red campion *Silene*

257    *dioica* and wild carrot *Daucus carota* were the most frequently sown species. Sixteen species

258    were sown at only one or two sites, reflecting tailoring of the seed mix to individual sites. Of the

259    36 sown non-cornfield annual species, three (chicory *Cichorium intybus*, red campion and ribwort

260    plantain *Plantago lanceolata*) were found at all sites where sown (although for chicory this was

261    only one site) and 16 were not recorded at any site where they were sown. The remaining species

262    varied in establishment success from one in nine sites for meadowsweet *Filipendula ulmaria*

263    (11% persistence), to seven out of eight sites for viper's-bugloss *Echium vulgare* (88%

264    persistence).

265    Total percent cover varied from 67% at BW to almost 220% at WC (Figure 2). For most

266    sites, the functional group that contributed most to the vegetation cover was forbs, with the

11

267  exception of LU and OP, which both had more grasses than forbs (Figure 2). Bryophyte cover

268  was variable between sites, with around half the sites surveyed having little or no bryophyte

269  cover and some having considerable amounts, in particular WC and OP, with 8% and 13%

270  respectively. Percent bare ground varied from zero at WC to almost 70% at TW.

271      Age of site and eight surface soil measures (pH, water, organic matter, total N, nitrate,

272  ammonium, total P, Olsen P) were tested for their relationship with nine vegetation

273  characteristics (total vegetation cover, forb cover, sown forb cover, unsown forb cover, grass

274  cover, bryophyte cover, bare ground, species richness and species diversity). Older sites had

275  significantly more grass cover and less bare ground (Figure 3). Surface soil total P was

276  significantly positively related to both grass cover and total vegetation cover (Figure 3).

277  Significantly greater bryophyte cover was also found at sites with higher surface soil nitrate

278  levels. Sites with wetter surface soils had significantly less bare ground. All three Grime's plant

279  strategies showed significant trends with age of site. Competitor (C) and stress tolerator (S)

280  scores both had a significant positive relationship with age of site, and ruderal scores (R) had a

281  significant negative relationship with age of site (Figure 4).

282

## Discussion

284

### Surface Soil Characteristics

286      Topsoil inversion had a significant impact on soil pH, organic matter, water content, and

287  both N and P content in the surface layer compared to control soils. Topsoil inversion raised soil

288  pH to approximately neutral levels, ideal for mesotrophic grassland creation. Different

289  communities of mesotrophic grassland have soil pH values that vary from pH 5.7 (MG13) to pH

290  7.5 (MG1) (Critchley et al. 2002). This suggests that the pH increase caused by deep ploughing

291  could be sufficient to modify the subsequent vegetation community development, although it may

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292   not directly affect plant species diversity (Janssens et al. 1998). There was no significant negative

293   correlation between age of site and difference in soil pH. An advantage of topsoil inversion is its

294   potential to achieve rapid changes in surface soil fertility, rather than waiting several decades for

295   natural processes to revert the soil to its pre-intensive agricultural condition (Marrs 1993). For

296   social and political reasons it is usually desirable that ecological restoration produces relatively

297   rapid results (Gilbert et al.  2003).

298        TI surface soils generally had lower water content than control surface soils. The

299   exception to this was CH, due to damaged land drains. This site aside, the decrease in surface soil

300   moisture caused by TI is likely to be a result of the reduction in water-retentive humus and the

301   decrease in vegetation cover, which would increase evaporation of water from the soil surface.

302   Older TI sites had closer soil water content to control soils, probably because they had developed

303   more vegetation cover which increased soil shading (Matthesen 1997).

304        Organic matter levels were generally lower in TI surface soils than controls. This is

305   similar to results found by Allison and Ausden (2004) for deep ploughing to 30 cm. This

306   indicates burial of topsoil which is strongly associated with high soil OM. Many nutrients are

307   associated with the topsoil, and this is reflected by the results for total N and total P, both of

308   which had significantly lower levels in surface TI soil than control soils for 12 of the 15 sites.

309   Results for extractable N and P were more variable, but in general sites had lower levels in TI

310   surface soils, which were significantly lower for at least five sites. The extreme right skew in the

311   data for nitrate and ammonium made analyses problematic, and some extremely high values

312   amongst mainly low values made the relationship between total and available N unclear. The rate

313   of N mineralization, which was not measured, would give a clearer picture of N availability to

314   plants (Gilbert & Anderson 1998). The data for Olsen P were less right-skewed, and total P

315   appears to have been a good predictor of Olsen P levels, which supports findings by others that

316   total P and Olsen P are well correlated (Pilgrim et al. 2007).

317     The results show that for many sites it is possible to lower surface soil N and P (total and

318     extractable) by topsoil inversion, which is often a central objective in restoration (Gilbert et al.

319     2003) and that this reduction can persist for at least 58 months. A survey of 40 UK restoration

320     sites found that high phosphorous concentration was detrimental to restoration (Fagan et al.

321     2008). A reduction in surface soil nutrients, particularly P, is essential to favour the growth of

322     less competitive plant species and enable the development of a diverse sward (Critchley et al.

323     2002).

324

325     **Plant Community Establishment**

326     Semi-natural grasslands in the UK are those with high species richness and managed at low

327     intensity by traditional techniques such as horse grazing. Although it has been shown that UK

328     semi-natural grassland diversity is generally associated with lower levels of soil nutrients

329     (Critchley et al. 2002), it does not seem to be the case for the early stages of habitat creation at

330     these trial sites. Higher levels of soil nutrients appear to favour an increase in plant cover due to

331     their enhancement of plant growth, and have no initial effect on plant diversity, suggesting that

332     species input from the seed rain has a more significant effect on species diversity. Seed rain is

333     likely to vary between sites according to their proximity to seed sources in the wider landscape,

334     and dispersal abilities of each species (Bakker et al. 1996). Species characteristic of semi-natural

335     grassland and associated with low soil fertility may not have been able to colonise from natural

336     sources at the survey sites. It is likely that all sites exhibited a much lower plant species diversity

337     than would have occurred if the ground had been conventionally prepared rather than deep

338     ploughed due to the reduction of the surface soil seed bank caused by topsoil burial. However it is

339     precisely this reduction in ground cover that is likely to favour successful restoration.

340     Establishment of specialist species by seeding has been shown to be more successful when bare

341 ground conditions are created prior to sowing, with more severe soil disturbances favouring faster

342 growth and reproduction of introduced specialist plants (Wagner et al. 2015).

343       The relationship between the number of sown species and the vegetation diversity at each

344 trial site is not straightforward. Introducing more species by sowing and planting did not result in

345 a more species-rich plant community, during the timescale of this study. The role of the seed mix

346 used in habitat creation and restoration schemes is much debated (Brand-Hardy 1996). It is

347 possible to tailor seed mixes to match a target NVC community, although this was not done in

348 this study. However, it appears from these results that the initial appearance and subsequent

349 survival of sown species is a stochastic process. At no sites were all introduced species present,

350 despite the young ages of all sites. The maximum introduced species persistence was 80% and for

351 nine sites was 50% or less. Individual species performance varied from 100% appearance to

352 complete absence. Wildflower seeds have not been subjected to artificial selection for good

353 viability, and wildflower seed quality is limited by the UK climate, which is not optimum for

354 seed ripening and harvesting. The seeds used at each site were not always of local provenance.

355 Using locally sourced seeds is thought to improve performance due to the genotypes being better

356 adapted to the local soil and weather conditions (Gilbert & Anderson 1998). There is also concern

357 that non-local strains could hybridise with local populations and erode their genetic

358 distinctiveness (Krauss & Kock 2004).

359       Poor-performing species may have specific germination requirements which were not met

360 at the site. Unless a target community is specified it is recommended that species chosen for a

361 seed mix are those which germinate easily over a wide range of conditions, using a mix including

362 mid- to late-successional species (Brand-Hardy 1996). Plug planting is sometimes recommended

363 for species that establish slowly from seed (Holden et al. 2003). However we found no evidence

364 of any of the species introduced by plug-planting in this study. This may be due to competition

365 from sown species, or to weather conditions such as drought that compromised their survival.

Cornfield annuals were sown to give the sites instant visual appeal and to act as a nurse crop. Nurse crops are used in restoration to improve the establishment of target species by providing shelter for seedlings during the early stages, and by suppressing weed growth (Walker et al. 2004). However the effectiveness of cover crops in improving performance of other sown species is unclear (Pywell et al. 2002). Although in this survey the nurse crop showed a significant decline in persistence over time, it is not clear whether it improved the establishment of other sown species or colonisation by specialist species, as there was no comparable control without a nurse crop. However, the visual element did serve to popularise the sites and involve local communities (Landlife 2008).

One unusual feature of the seed mixes used was the lack of grass species. At the fourteen sites that were sown, only one of these (LU) included grasses in the seed mix, and even here the species used (red fescue *Festuca rubra* and sheep's fescue *Festuca ovina*) were chosen as standard forestry mixes. It is usually recommended that grasses form 70 to 80% of the seed mix (by seed numbers) for a meadow creation scheme (Holden et al. 2003). The low grass cover at the survey sites is likely to be a result of their non-inclusion in the seed mix, although grasses had colonised relatively easily from the seed rain. Sowing a mixture of forbs may therefore improve the overall species diversity of the new habitat by allowing forbs to establish early on in the absence of grasses. Fagan et al. (2008) recommend that seed mixes used to restore calcareous grassland should aim to prevent assembly of low-value communities dominated by grasses. It is usually the presence of many forb species that is used to judge the relative species richness of grassland habitats, rather than the number of grass species (Rodwell 2006). Reduction or elimination of grass seeds in restoration seed mixes may therefore be a positive step towards improving restoration success.

Results from the NVC analysis showed that the survey sites were closest to a range of semi-natural habitats, including disturbed ground, mesotrophic grasslands, upland acidic

16

391 grassland and sand dune communities. The fit of the NVC to the vegetation data was generally

392 poor, and it was not possible to assign NVC communities manually using tables due to the

393 dissimilarity of the observed species compositions with those listed. Many of the constant species

394 were absent. The survey sites are relatively young artificially created habitats, none of which had

395 any specific NVC restoration goal, and they do not closely resemble any semi-natural habitat.

396 Many attempts at restoring or creating species-rich semi-natural grassland highlight the

397 importance of selecting sites with low soil fertility, in particular P (Öster et al. 2009). The results

398 from this survey show that where this is not possible, soil fertility can be reduced by the use of

399 topsoil inversion to bury topsoil under the lower-fertility subsoil. It is notable that none of the

400 topsoil inversion sites had a management plan such as a mowing or grazing regime, which would

401 have the potential to influence plant community development. However, it is clear from this

402 evaluation of 15 sites that topsoil inversion can significantly aid the establishment of a new, more

403 species-rich community by creating a lower-fertility substrate to begin habitat creation or

404 restoration. We will next focus on data from a replicated field experiment that investigates

405 detailed changes to soil profile chemistry before and after topsoil inversion in comparison to

406 conventional ploughing, and follows the development of plant communities during three growing

407 seasons post-restoration.

408

# **Acknowledgements**

412

# **Literature Cited**

414

415    Allen SE (ed.) (1989) Chemical Analysis of Ecological Materials. Second edition. Blackwell

416    Scientific Publications

417

418    Allison M, Ausden, M (2004) Successful use of topsoil removal and soil amelioration to create

419    heathland vegetation. Biological Conservation 120:225-232

420

421    Bakker JP, Poschlod P, Strykstra RJ, Bekker RM, Thompson K (1996) Seed banks and seed

422    dispersal: important topics in restoration ecology. Acta Botanica Neerlandica 45:461-490

423

424    Ball DF (1964) Loss-on-ignition as an estimate of organic matter and organic carbon in non-

425    calcareous soils. Journal of Soil Science 15:84-92

426

427    Brand-Hardy R (1996) Seed mixtures for reversion of arable land to species-rich grassland.

428    Ministry of Agriculture, Fisheries and Food Final Project Report

429

430    Carroll JA, Caporn SJM, Johnson D, Morecroft MD, Lee JA (2003) The interactions between

431    plant growth, vegetation structure and soil processes in semi-natural acidic and calcareous

432    grasslands receiving long-term inputs of simulated pollutant nitrogen deposition. Environmental

433    Pollution 121:363-376

434

435    Clarke CT (1997) Role of Soils in Determining Sites for Lowland Heathland Reconstruction in

436    England. Restoration Ecology 5:256-264

437

438    Critchley CNR, Chambers BJ, Fowbert JA, Sanderson RA, Bhogal A, Rose SC (2002)

439    Association between lowland grassland plant communities and soil properties. Biological

440    Conservation 105:199-215

441

442    Fagan KC, Pywell RF, Bullock JM, Marrs RH (2008) Do restored calcareous grasslands on

443    former arable fields resemble ancient targets? The effect of time, methods and environmental

444    outcomes. Journal of Applied Ecology 45:1293-1303

445

446    Gilbert OL, Anderson P (1998) Habitat Creation and Repair. Oxford University Press

447

448    Gilbert JC, Higginbottom PRG, Gowing DJG, Bradley RI, Kerr DM, Leeds-Harrison PB, Spoor

449    G, Godwin RJ (1996) The habitat creation model. A model to assess the viability of converting

450    arable land into semi-natural habitat. MAFF Commissioned Project CSA 2373. UK: Cranfield

451    University

452

453    Gilbert JC, Gowing DJG, Bullock RJ (2003) Influence of seed mixture and hydrological regime

454    on the establishment of a diverse grassland sward at a site with high phosphorous availability.

455    Restoration Ecology 11:424-435

456

457    Glen E (2009) Evaluation of Topsoil Inversion for Habitat Creation or Restoration. PhD

458    dissertation, Manchester Metropolitan University, UK

459

460    Holden C, Bradley B, Brookes N (2003) Habitat creation guide for lowland Derbyshire.

461    Derbyshire Wildlife Trust, UK

462

463  Hutchings MJ, Booth KD (1996) Studies on the feasibility of re-creating chalk grassland

464  vegetation on ex-arable land. I. The potential roles of the seed bank and seed rain. Journal of

465  Applied Ecology 33:1171-1181

466

467  Janssens F, Peeters A, Tallowin JRB, Bakker JP, Bekker RM, Fillat F, Oomes MJM (1998)

468  Relationship between soil chemical factors and grassland diversity. Plant and Soil 202:69-78

469

470  Jones L, Stevens C, Rowe EC, Payne R, Caporn SJM, Evans CD, Field C, Dale S (in press). Can

471  on-site management mitigate nitrogen deposition impacts? Biological Conservation

472

473  Jones MLM, Norman K, Rhind PM (2010) Topsoil inversion as a restoration measure in sand

474  dunes, early results from a UK field-trial. Journal of Coastal Conservation 14:139-151

475

476  Krauss SL, Koch JM (2004) Rapid genetic delineation of provenance for plant community

477  restoration. Journal of Applied Ecology 41:1162-1173

478

479  Landlife (2008) Soil Inversion Works: breaking new ground in creative conservation. Landlife,

480  Knowsley, UK

481

482  Lawson CS, Ford M, Mitchley J, Warren JM (2004) The establishment of heathland vegetation

483  on ex-arable land: the response of *Calluna vulgaris* to soil acidification. Biological Conservation

484  116:409-416

485

486  Marrs RH (1993) Soil Fertility and Nature Conservation in Europe: Theoretical Considerations

487  and Practical Management Solutions. Advances in Ecological Research 24:241-300

488

489     Marrs R (2002) Manipulating the chemical environment of the soil. Chapter 9 In: Perrow MR,

490     Davy AJ (eds) Handbook of Ecological Restoration Volume 1: Principles of Restoration.

491     Cambridge University Press, Cambridge, UK

492

493     Marrs RH, Gough MW (1989) Soil fertility - a potential problem for habitat restoration. Chapter

494     4 In: Buckley GP (ed) Biological Habitat Construction. John Wiley & Sons Ltd, UK

495

496     Marrs RH, Snow CSR, Owen KM, Evans CE (1998) Heathland and acid grassland creation on

497     arable soils at Minsmere: identification of potential problems and a test of cropping to impoverish

498     soils.  Biological Conservation 85:69-82

499

500     Matthesen P, Damgaard C (1997) Reolpløjning [Deep ploughing]. Videnblade Park-og

501     Landsabsserien no. 4.1-3. August

502

503     Öster M, Ask K, Cousins SAO, Eriksson O (2009) Dispersal and establishment limitation reduces

504     the potential for successful restoration of semi-natural grassland communities on former arable

505     fields. Journal of Applied Ecology 46:1266-1274

506

507     Pilgrim ES, Smith RS, Bardgett RD, Mortimer SR, Beaumont DA, Millward D, Lawson C,

508     Harrison KA, Edwards AE, Quirk H, Tallowin JRB (2007) Establishing links between floral

509     diversity and soil phosphorous availability over a range of different grasslands. In: Hopkins JJ

510     (ed) High value grassland: providing biodiversity, a clean environment and premium products pp.

511     297-300. British Grassland Society Occasional Symposium No. 38. British Grassland Society

512

513 Pywell RF, Bullock JM, Hopkins A, Walker KJ, Sparks TH, Burke MJW, Peel S (2002)

514 Restoration of species-rich grassland on arable land: assessing the limiting processes using a

515 multi-site experiment. Journal of Applied Ecology 39:294-309

516

517 Rodwell JS (ed) (1992) British Plant Communities, Volume 3 Grasslands and Montane

518 Communities. Cambridge University Press, UK

519

520 Rodwell JS (2006) National Vegetation Classification: Users' handbook. JNCC, UK

521

522 Rowell DL (1994) Soil Science: Methods & Applications. Longman Scientific and Technical,

523 UK

524

525 Sykes J M, Lane A J (eds) (1996) The UK Environmental Change Network Protocols for

526 Standard Measurements of Terrestrial Sites. The Stationery Office, UK

527

528 Wagner M, Bullock JM, Hulmer L, Hulmes S, Peyton J, Amy SR, Savage J, Tallowin J, Heard

529 MS, Pywell RF (2015) Creation of micro-topographic features: a new tool for introducing

530 specialist species of calcareous grassland to restored sites? Applied Vegetation Science.

531 doi: 10.1111/avsc.12198

532

533 Walker KJ, Stevens PA, Stevens DP, Mountford JO, Manchester S, Pywell RF (2004) The

534 restoration and re-creation of species-rich lowland grassland on land formerly managed for

535 intensive agriculture in the UK. Biological Conservation 119:1-18

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554 **Table 1.** Summary of survey sites showing date of topsoil inversion, age of site at the time of the

555 survey (time since topsoil inversion), numbers of plant species sown and plug planted, and use of

556 cornfield annual nurse crops.

| Site Code | Date of topsoil inversion | Time since topsoil inversion | Number of species sown | Number of species plug planted | Cornfield annual nurse crop? |
|---|---|---|---|---|---|
| BH | 03/03 | 52 | 25 | 0 | Yes |
| BW | 08/05 | 23 | 12 | 0 | Yes |
| CD | 01/04 | 39 | 0 | 0 | No |
| CH | 02/06 | 17 | 14 | 0 | Yes |
| CR | 08/05 | 23 | 10 | 2 | Yes |
| CW | 08/05 | 23 | 13 | 0 | Yes |
| EP | 11/02 | 56 | 15 | 0 | Yes |
| FW | 08/05 | 23 | 12 | 4 | Yes |
| HH | 12/05 | 19 | 18 | 1 | Yes |
| LU | 09/02 | 58 | 15 | 0 | Yes |
| OP | 11/02 | 57 | 16 | 0 | Yes |
| PM | 12/03 | 43 | 14 | 0 | Yes |
| PT | 08/05 | 23 | 12 | 0 | Yes |
| TW | 01/07 | 6 | 18 | 0 | Yes |
| WC | 09/03 | 46 | 28 | 0 | Yes |

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562 **Table 2.** Comparisons between control and topsoil inversion (TI) surface soil at 15 topsoil

563 inversion sites for surface soil pH, soil moisture and soil organic matter (OM) content, using t-

564 tests. *, significant at the 5% level; **, significant at the 1% level; ***, significant at the 0.1%

565 level; N = 5; df adjusted to account for unequal variances.

566

| Site | Mean soil pH | | *t-value* | Mean soil water (%) | | *t-value* | Mean soil OM (% LOI) | | *t-value* |
|------|---------|------|---------|---------|------|-----------|---------|------|--------|
| | Control | TI | | Control | TI | | Control | TI | |
| BH | 6.06 | 6.31 | -2.32 | 30.9 | 22.0 | 3.27* | 12.03 | 5.20 | 4.92*** |
| BW | 6.28 | 7.82 | -9.75*** | 29.1 | 12.4 | 5.61** | 10.11 | 1.84 | 28.24*** |
| CD | 5.61 | 5.91 | -2.96* | 27.0 | 6.4 | 11.85*** | 7.35 | 0.32 | 11.38*** |
| CH | 7.23 | 7.46 | -2.38 | 15.8 | 20.2 | -2.86* | 1.86 | 1.45 | 0.87 |
| CR | 6.72 | 7.27 | -5.99*** | 35.3 | 16.7 | 3.64*** | 10.34 | 1.62 | 6.43*** |
| CW | 6.43 | 7.20 | -6.31*** | 24.5 | 15.9 | 5.20*** | 5.27 | 1.66 | 9.85*** |
| EP | 6.38 | 6.72 | -2.42* | 30.7 | 22.7 | 3.32* | 8.00 | 5.72 | 2.56 |
| FW | 6.22 | 7.12 | -3.60* | 24.1 | 14.6 | 5.53*** | 4.98 | 1.43 | 8.53*** |
| HH | 6.58 | 6.80 | -1.23 | 20.2 | 10.3 | 6.29*** | 6.22 | 4.05 | 2.33 |
| LU | 6.04 | 6.04 | 0.04 | 17.3 | 17.1 | 0.11 | 2.84 | 1.05 | 6.42*** |
| OP | 6.34 | 6.87 | -1.84 | 22.5 | 19.2 | 4.22*** | 4.16 | 2.58 | 3.19* |
| PM | 5.37 | 6.64 | -8.94 | 24.8 | 23.0 | 1.43 | 6.96 | 3.59 | 9.34*** |
| PT | 6.75 | 7.51 | -3.51** | 35.5 | 9.6 | 10.33*** | 11.62 | 2.15 | 10.52*** |
| TW | 5.93 | 6.80 | -7.09*** | 19.7 | 8.0 | 6.36*** | 4.88 | 1.15 | 8.19*** |
| WC | 6.85 | 7.15 | -1.99 | 17.0 | 14.2 | 1.09 | 2.84 | 1.97 | 1.69 |

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**Table 3.** Comparisons between control and topsoil inversion (TI) surface soil at 15 topsoil inversion sites for total N, nitrate, ammonium, total P and Olsen (extractable) P content, using t-tests (total N and P; Olsen P) and Mann-Whitney tests (nitrate and ammonium). Asterisks (*, **, and ***) indicate significance at the 5, 1, and 0.1% level, respectively; N = 5 and df adjusted to account for unequal variances.

| Site | Mean total N (mg/g) | | t-value | Median nitrate (mg/kg) | | W | Median ammonium (mg/kg) | | W | Mean total P (mg/g) | | t-value | Mean Olsen P (mg/kg) | | t-value |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Control | TI | | Control | TI | | Control | TI | | Control | TI | | Control | TI | |
| BH | 5.65 | 2.23 | 6.79*** | 154.22 | 1.32 | 40.0* | 1.84 | 2.54 | 27.0 | 0.97 | 0.62 | 5.03** | 7.09 | 14.58 | -3.56* |
| BW | 3.94 | 0.59 | 13.97*** | 3.80 | 0.48 | 40.0* | 2.50 | 0.65 | 40.0* | 0.73 | 0.16 | 19.59*** | 16.69 | 0.57 | 5.60*** |
| CD | 3.68 | 0.25 | 13.76*** | 0.54 | 0.44 | 29.0 | 14.52 | 0 | - | 0.67 | 0.10 | 9.03*** | 9.24 | 3.68 | 8.00*** |
| CH | 1.44 | 1.54 | -0.36 | 0.52 | 0.42 | 31.0 | 0.90 | 1.00 | 25.0 | 0.36 | 0.16 | 2.32 | 17.11 | 3.12 | 3.02* |
| CR | 4.03 | 1.06 | 5.26*** | 1.16 | 0.29 | 40.0* | 4.97 | 0.72 | 40.0* | 0.67 | 0.33 | 4.33*** | 22.45 | 3.22 | 21.48*** |
| CW | 2.43 | 0.83 | 8.99*** | 7.33 | 0 | - | 0.62 | 0.20 | 30.0 | 0.55 | 0.36 | 2.45* | 33.22 | 5.81 | 5.66*** |
| EP | 5.44 | 3.48 | 3.24* | 21.20 | 7.06 | 35.0 | 2.07 | 0.57 | 38.0* | 1.03 | 0.90 | 1.36 | 6.81 | 11.62 | -3.69** |
| FW | 2.72 | 0.85 | 6.63*** | 12.56 | 0.25 | 37.0 | 0.15 | 0.00 | 32.0 | 0.72 | 0.41 | 3.10* | 81.60 | 8.11 | 6.90*** |
| HH | 2.96 | 1.26 | 3.44* | 0.61 | 0.00 | 33.0 | 0.57 | 0.47 | 34.0 | 0.72 | 0.19 | 10.31*** | 27.74 | 4.89 | 9.34*** |
| LU | 1.60 | 0.59 | 16.53*** | 0.78 | 0.32 | 37.0 | 1.20 | 0.34 | 30.0 | 0.41 | 0.16 | 5.59*** | 16.86 | 12.40 | 1.98 |
| OP | 1.67 | 1.09 | 2.49 | 35.78 | 11.36 | 35.0 | 3.50 | 1.26 | 38.0* | 0.62 | 0.52 | 0.93 | 45.43 | 35.99 | 1.36 |
| PM | 3.79 | 2.40 | 5.22*** | 91.54 | 0.99 | 40.0* | 2.31 | 0.00 | 33.5 | 0.81 | 0.41 | 3.64* | 21.10 | 4.28 | 2.15 |
| PT | 6.15 | 1.04 | 9.81*** | 16.93 | 1.59 | 37.0 | 2.45 | 0.50 | 35.0 | 0.92 | 0.21 | 6.63** | 15.84 | 2.66 | 4.32*** |
| TW | 3.28 | 0.98 | 10.59*** | 30.40 | 0.69 | 40.0* | 1.42 | 0.72 | 38.0* | 0.87 | 0.36 | 6.69* | 21.79 | 27.06 | -0.89 |
| WC | 1.24 | 0.70 | 2.28 | 14.40 | 18.59 | 29.0 | 1.30 | 0.57 | 37.0 | 0.46 | 0.28 | 3.54* | 27.44 | 22.94 | 1.18 |

590 **Table 4.** Age of site (months since topsoil inversion) and plant species and community outcomes

591 on inverted soil at each of the 15 topsoil inversion survey sites. Number of non-woody species

592 recorded shown separated into functional groups (grasses includes sedges and rushes; ferns

593 includes horsetails). Numbers in parentheses show of which were introduced (sown or planted)

594 species. No species were introduced at CD. NVC communities derived from all species recorded

595 within topsoil inversion area.

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| Site | Age (months) | Number of species recorded | | | | | NVC |
|------|------|------|------|------|------|------|------|
| | | Forbs | Grasses | Ferns | Bryophytes | Total | |
| BH | 52 | 20 (2) | 4 | 0 | 0 | 24 (2) | MG6 |
| BW | 23 | 16 (4) | 4 | 0 | 1 | 21 (4) | MG5 |
| CD | 39 | 25 | 5 | 0 | 3 | 33 | U4 |
| CH | 17 | 42 (12) | 6 | 0 | 1 | 49 (12) | MG5 |
| CR | 23 | 28 (8) | 7 | 1 | 1 | 37 (8) | MG6 |
| CW | 23 | 27 (11) | 4 | 0 | 1 | 32 (11) | MG1 |
| EP | 56 | 41 (8) | 3 | 0 | 0 | 44 (8) | MG5 |
| FW | 23 | 16 (6) | 6 | 0 | 1 | 23 (6) | MG1 |
| HH | 19 | 19 (9) | 4 | 1 | 0 | 24 (9) | OV19 |
| LU | 58 | 19 (7) | 3 | 0 | 3 | 25 (7) | SD8 |
| OP | 57 | 23 (6) | 8 | 1 | 3 | 35 (6) | MG1 |
| PM | 43 | 21(7) | 5 | 0 | 1 | 27 (7) | MG5 |
| PT | 23 | 20 (5) | 5 | 0 | 1 | 26 (5) | OV23 |
| TW | 6 | 21 (9) | 1 | 0 | 0 | 21 (9) | OV22 |
| WC | 46 | 37 (16) | 6 | 0 | 1 | 44 (16) | MG1 |

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602 **Table 5.** Total number of species sown and planted at each of the 15 topsoil inversion survey

603 sites, and number of these recorded during the survey. Numbers in parentheses show of which

604 were cornfield annual species. Creative conservation seed mixes and plug plants were used which

605 comprised of 100% forbs.

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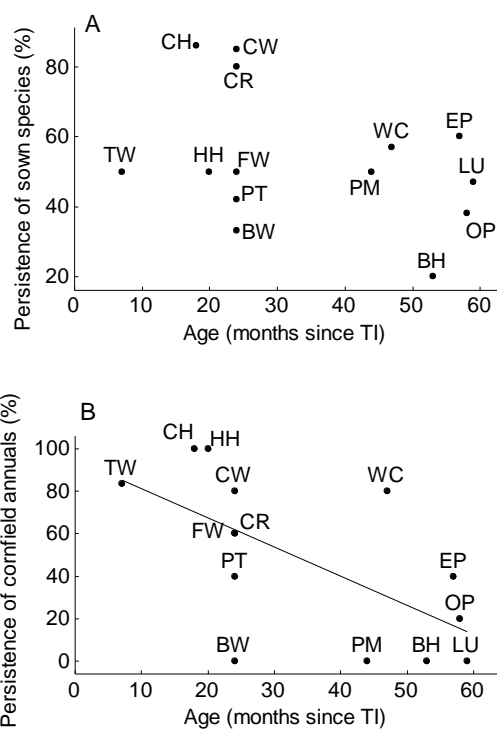| Site | Age | Number of spp. | | Number recorded spp. | | Persistence (%) |
|------|-----|------|--------|------|--------|------|
| | (months) | Sown | Planted | Sown | Planted | |
| BH | 52 | 25 (2) | 0 | 5 (0) | - | 20 |
| BW | 23 | 12 (5) | 0 | 4 (0) | - | 33 |
| CD | 39 | 0 | 0 | - | - | - |
| CH | 17 | 14 (5) | 0 | 12 (5) | - | 86 |
| CR | 23 | 10 (5) | 2 | 8 (3) | 0 | 80 |
| CW | 23 | 13 (5) | 0 | 11 (4) | - | 85 |
| EP | 56 | 15 (5) | 0 | 9 (2) | - | 60 |
| FW | 23 | 12 (5) | 4 | 6 (3) | 0 | 50 |
| HH | 19 | 18 (6) | 1 | 9 (6) | 0 | 50 |
| LU | 58 | 15 (1) | 0 | 7 (0) | - | 47 |
| OP | 57 | 16 (5) | 0 | 6 (1) | - | 38 |
| PM | 43 | 14 (5) | 0 | 7 (0) | - | 50 |
| PT | 23 | 12 (5) | 0 | 5 (2) | - | 42 |
| TW | 6 | 18 (6) | 0 | 9 (5) | - | 50 |
| WC | 46 | 28 (5) | 0 | 16 (4) | - | 57 |

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**Figure 1.** Persistence of A) all sown species and B) sown cornfield annual species (percentage of introductions recorded) as related to age of site in months since topsoil inversion (TI). The relationship was only significant for cornfield annuals: $R^2 = 34.7\%$, $P = 0.016$.
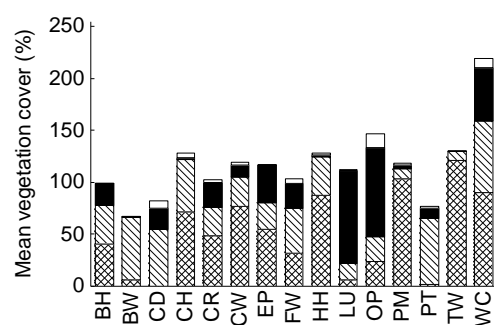
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**Figure 2.** Mean percent cover of vegetation in deep ploughed soil for the 15 topsoil inversion

survey sites (N=5/site). Sites are identified by their unique codes. Cross hatched = sown forbs;

hatched = naturally colonised forbs; black = grasses, sedges and rushes; white = ferns, horsetails
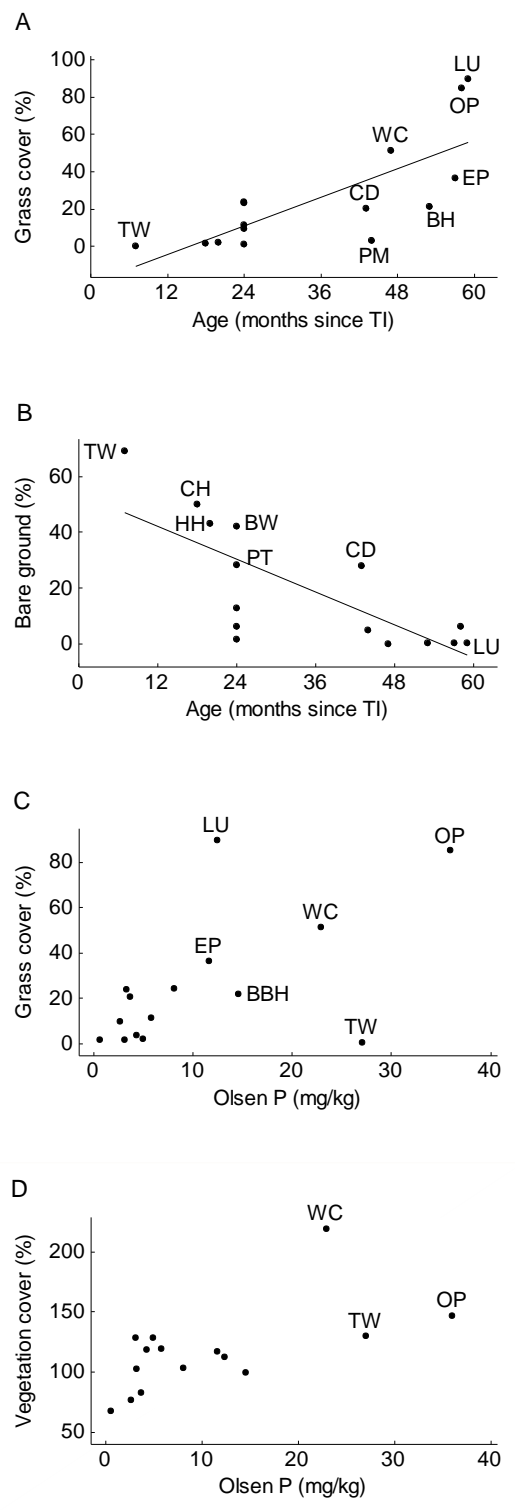
and bryophytes.

A



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C



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D



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**Figure 3.** Significant regressions and correlations between A) age [months since topsoil

inversion] and grass cover, B) age [months since topsoil inversion] and percent bare ground, C)

Olsen P and grass cover and D) Olsen P and total vegetation cover from the 15 topsoil inversion

657  survey sites. A: $R^2$=53.8, P=0.001; B: $R^2$=52.7, P=0.001; C: r=0.585, P=0.022; D: r=0.614,

658  P=0.015.



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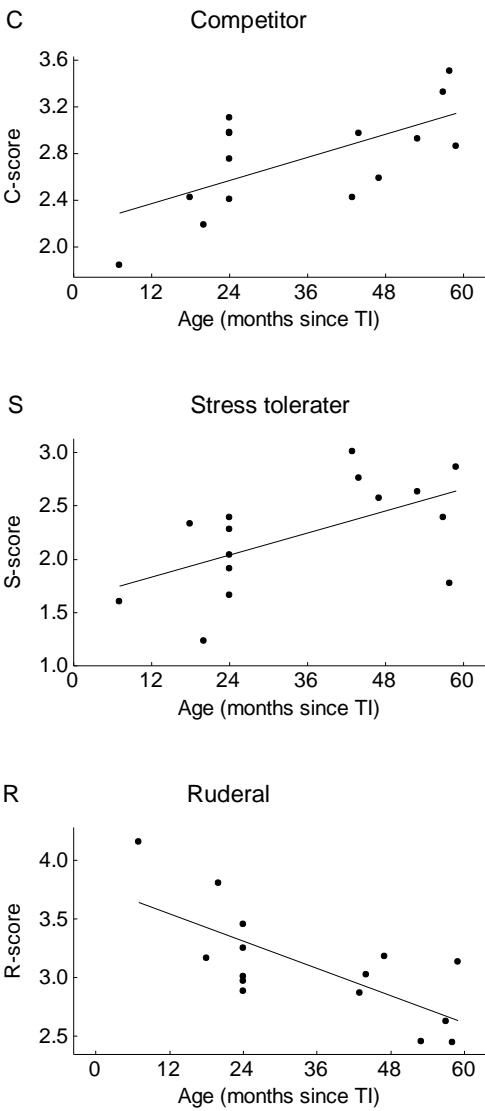
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662  **Figure 4.** Significant regressions between age of site (months since topsoil inversion) and

663  Grime's plant strategies scores (C=Competitor; S=Stress tolerator; R=Ruderal) from the 15

664  topsoil inversion survey sites. Competitor: $R^2$=36.4%, *P*=0.010; Stress tolerator: $R^2$=27.9%,

665  *P*=0.025; Ruderal: $R^2$=48.5%, *P*=0.002.

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668 **Supplementary Material**

669 **Table S1.** Topsoil inversion survey site codes, names, GPS locations (latitude and longitude) date of deep ploughing (month/year), partner

670 organisation(s) and the objective of using deep ploughing at each site in terms of habitat creation or other general aim.

671

| Site code | Site name | GPS location | Date deep ploughed | Partner organisation(s) | Objective |
|-----------|-----------|--------------|--------------------|-------------------------|-----------|
| BH | Billa Barra Hill | 52.699630, -1.312536 | 3/03 | National Forest | Creation of wildflower meadow adjacent to woodland on former arable land |
| BW | Burrough's Wood | 52.651050, -1.265638 | 8/05 | Woodland Trust | Creation of woodland edge / meadow habitat adjacent to a new wood on former arable land |
| CD | Carloggas Down | 50.374101, -4.791875 | 1/04 | Cornish Heathland Project / English Nature | Trial the success of deep ploughing China clay waste overlaid with imported topsoil as a means of creating heathland habitat on China clay waste spoil heaps |
| CH | Cowick Hall | 53.683002, -1.006788 | 2/06 | Woodland Trust | Creation of wildflower meadow on former arable land |

| Site code | Site name | GPS location | Date deep ploughed | Partner organisation(s) | Objective |
|---|---|---|---|---|---|
| CR | Centenary Royal Tigers Wood | 52.657109, -1.329191 | 8/05 | Woodland Trust | Creation of woodland edge / meadow habitat adjacent to a new wood on former arable land |
| CW | Coton Wood | 52.729180, -1.637238 | 8/05 | Woodland Trust | Creation of woodland edge / meadow habitat adjacent to a new wood on former arable land |
| EP | Eden Project | 50.359898, -4.740167 | 11/02 | Eden Project | Loosen compacted topsoil heaps which were removed from building areas and deposited onto former arable land, to create meadow habitat |
| FW | Foxley Wood | 52.747622, -1.588158 | 8/05 | Woodland Trust | Creation of woodland edge / meadow habitat adjacent to a new wood on former arable land |
| HH | Hedley Hall Wood | 54.900945, -1.662938 | 12/05 | Woodland Trust | Creation of woodland edge / meadow habitat adjacent to a new wood on former arable land |
| LU | Lunt | 53.506511, -2.989687 | 9/02 | Forest Enterprise | Creation of woodland / woodland edge / meadow habitat on former arable land |

| Site code | Site name | GPS location | Date deep ploughed | Partner organisation(s) | Objective |
|---|---|---|---|---|---|
| OP | Old Pale Farm, Delamere Forest | 53.223993, -2.684681 | 11/02 | Forest Enterprise | Creation of wildflower meadow on former arable land |
| PM | Paddington Meadow | 53.391046, -2.553761 | 12/03 | | Creation of wildflower meadow on former arable land on flood plain adjacent to river |
| PT | Pear Tree Wood | 52.655066, -.1258530 | 8/05 | Woodland Trust | Creation of woodland edge / meadow habitat adjacent to a new wood on former arable land |
| TW | Thorn Wood | 53.252795, -2.562195 | 1/07 | Woodland Trust | Creation of woodland edge / meadow habitat adjacent to a new wood on former arable land |
| WC | Wheeldon Copse | 53.255148, -2.745293 | 9/03 | Woodland Trust | Creation of woodland / woodland edge / meadow habitat on former arable land |

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675    **Table S2.** Summary of plant species introduced at the 15 TI survey sites (separated into sown

676    cornfield annuals, sown other species, and plug planted), showing number of sites introduced

677    at, number of sites recorded at during the survey, and percentage persistent introductions

678    (recorded species as a percentage of introduced). This does not include species recorded at

679    sites where they were not introduced. Some species were both sown and planted; these

680    species are included twice and tallied separately. Names according to Stace (2010).

681

| Species | | Number of sites | | % persistent introductions |
|---|---|---|---|---|
| | | Introduced | Recorded | |
| Sown: | | | | |
| Cornfield Annuals | | | | |
| | *Agrostemma githago* Corncockle | 13 | 9 | 69 |
| | *Anthemis arvensis* Corn chamomile | 12 | 5 | 42 |
| | *Centaurea cyanus* Cornflower | 13 | 8 | 62 |
| | *Chrysanthemum segetum* Corn marigold | 13 | 7 | 54 |
| | *Papaver rhoeas* Common poppy | 13 | 5 | 38 |
| | *Spergula arvensis* Corn spurrey | 2 | 1 | 50 |
| | | | | |
| Sown: | | | | |
| Other | *Achillea millefolium* Yarrow | 3 | 2 | 67 |
| | *Agrimonia eupatoria* Common agrimony | 2 | 0 | 0 |
| | *Alliaria petiolata* Garlic mustard | 3 | 0 | 0 |
| | *Anthriscus sylvestris* Cow parsley | 2 | 1 | 50 |
| | *Anthyllis vulneraria* Kidney vetch | 5 | 3 | 60 |
| | *Campanula trachelium* Nettle-leaved bellflower | 3 | 0 | 0 |
| | *Centaurea nigra* Common knapweed | 12 | 10 | 83 |
| | *Cichorium intybus* Chicory | 1 | 1 | 100 |
| | *Daucus carota* Wild carrot | 13 | 10 | 77 |
| | *Digitalis purpurea* Foxglove | 4 | 1 | 25 |
| | *Dipsacus fullonum* Wild teasel | 2 | 0 | 0 |
| | *Echium vulgare* Viper's-bugloss | 8 | 7 | 88 |
| | *Filipendula ulmaria* Meadowsweet | 9 | 1 | 11 |

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| 707 | | *Galium mollugo* Hedge bedstraw | 2 | 0 | 0 |
|------|---------|----------------------------------------------------|----|----|-----|
| 708 | | *Galium verum* Lady's bedstraw | 7 | 3 | 43 |
| 709 | | *Geranium pratense* Meadow cranesbill | 2 | 0 | 0 |
| 710 | | *Geum rivale* Water avens | 1 | 0 | 0 |
| 711 | | *Geum urbanum* Wood avens | 2 | 0 | 0 |
| 712 | | *Hyacinthoides non-scripta* Bluebell | 3 | 0 | 0 |
| 713 | | *Hypericum perforatum* Perforate St John's-wort | 1 | 0 | 0 |
| 714 | | *Iris pseudacorus* Yellow iris | 1 | 0 | 0 |
| 715 | | *Knautia arvensis* Field scabious | 14 | 5 | 36 |
| 716 | | *Leucanthemum vulgare* Oxeye daisy | 9 | 7 | 78 |
| 717 | | *Malva moschata* Musk mallow | 2 | 1 | 50 |
| 718 | | *Oenothera biennis* Evening-primrose | 3 | 1 | 33 |
| 719 | | *Plantago lanceolata* Ribwort plantain | 5 | 5 | 100 |
| 720 | | *Primula veris* Cowslip | 5 | 0 | 0 |
| 721 | | *Prunella vulgaris* Self-heal | 4 | 3 | 75 |
| 722 | | *Ranunculus acris* Meadow buttercup | 9 | 6 | 67 |
| 723 | | *Reseda luteola* Weld | 1 | 0 | 0 |
| 724 | | *Rhinanthus minor* Yellow-rattle | 2 | 1 | 50 |
| 725 | | *Sanguisorba minor* Salad burnet | 1 | 0 | 0 |
| 726 | | *Silene dioica* Red campion | 10 | 10 | 100 |
| 727 | | *Silene latifolia* White campion | 2 | 1 | 50 |
| 728 | | *Stachys officianalis* Betony | 1 | 0 | 0 |
| 729 | | *Succisa pratensis* Devil's-bit scabious | 8 | 0 | 0 |
| 730 | | | | | |
| 731 | Planted | *Campanula trachelium* Nettle-leaved bellflower | 1 | 0 | 0 |
| 732 | | *Centaurea nigra* Common knapweed | 1 | 0 | 0 |
| 733 | | *Glechoma hederacea* Ground-ivy | 2 | 0 | 0 |
| 734 | | *Iris pseudacorus* Yellow iris | 1 | 0 | 0 |
| 735 | | *Primula veris* Cowslip | 1 | 0 | 0 |
| 736 | | *Primula vulgaris* Primrose | 2 | 0 | 0 |
| 737 | | | | | |

738
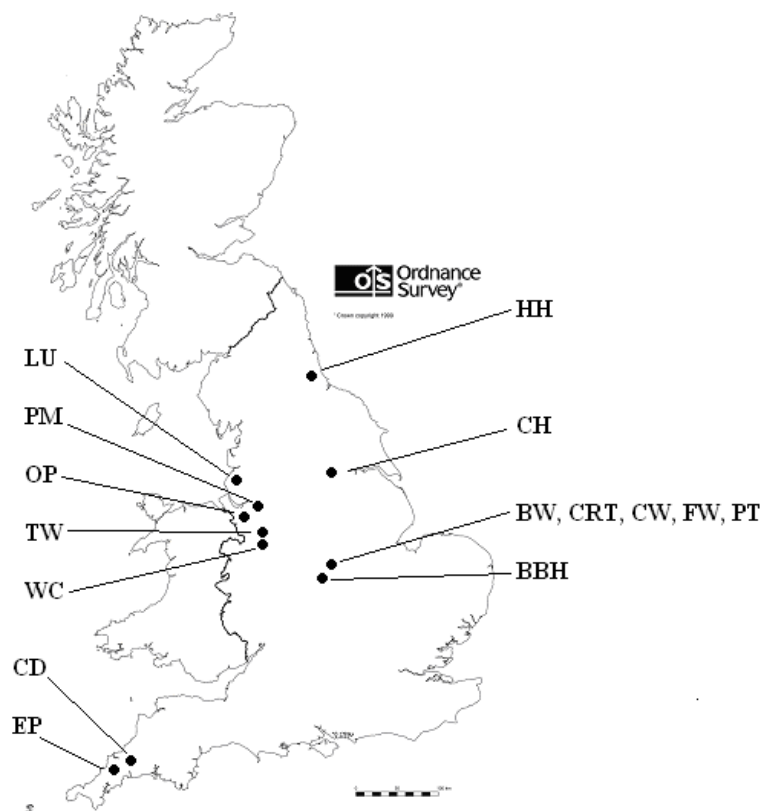
**Figure S1.** Approximate locations of the fifteen topsoil inversion survey sites. Sites are

represented by unique codes, used throughout this work. Five sites (BW, CRT, CW, FW, PT)

are in close proximity, and these have been shown as one point. For site names, see Table S1.

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