Reducing soil fertility to enable ecological restoration: a new method to test the efficacy of Full-Inversion Tillage

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ABSTRACT

Ecological restoration of high-quality, semi-natural communities of conservation value on ex-arable soils with raised fertility has been a major problem in northern Europe. One suggested way of tackling this problem is to use Full-Inversion Tillage (FIT) where the fertile top-soil is moved below infertile sub-surface layers. This should provide infertile conditions at least in the short- to medium-term for the establishment of communities that require these conditions. Here, we pioneer a rigorous test of the efficacy of this approach. Our new method, using Principal Response Curves (PRCs), overcomes the difficulty in testing for change in soil physico-chemical properties down soil profiles with the inherent problem of autocorrelations between soil layers. Principal Response Curves (PRCs) is a multivariate technique, usually used to test for effects of treatment effects through time on a community matrix. We propose an extension of their use for the multivariate analysis of properties down a soil-depth profile. We tested the effects of FIT in two contrasting soils, before and after treatment. In a clay loam soil, FIT was effective in reducing the soil fertility in the surface 12 cm. Indeed the soil available P concentration, a key variable, was more than halved in the surface layers, and was below the lowest literature target threshold for the establishment of semi-natural grassland. In contrast, in the sandy soil, soil properties increased throughout the profile after FIT, primarily because of the pre-treatment nutrient distribution within the soil. Before FIT treatment, the maximum concentrations of most measured variables were at mid-depth and FIT redistributed these to the surface and bottom layers. Our results demonstrate the potential for FIT in ecological restoration, but indicate that its efficacy depends on soil type and the site history. We recommend that in future a pre-treatment assessment of soil properties with depth is undertaken before FIT is implemented, and that afterwards our PRC approach can be used to test efficacy immediately after treatment, and has the potential for measuring soil resilience to perturbation through time.

*Key Words:*

Soil Inversion

Soil Impoverishment

Multivariate Analysis

Soil Fertility

Conservation

Resilience

## Introduction

The spread and intensification of agricultural land use has been a major cause of biodiversity decline (Balmford et al., 2012), indeed, in northern Europe the effects of increased soil fertility is well known to prevent the restoration of semi-natural communities such as species-rich grasslands of high conservation interest (Wells, 1980; Marrs, 1993). Part of the reason for this is that most semi-natural plant communities of northern Europe require infertile conditions and that when soil conditions become more fertile through a combination of processes, i.e. through successional processes (Odum, 1971; Gorham et al., 1979), elevated atmospheric inputs (especially N) (Diemont and Heil, 1984; Maskell et al., 2010; Armitage et al., 2012) and fertilizer additions (Digby and Kempton, 1987), species diversity reduces through competitive effects brought about by the increased dominance of a few species (Grime, 1979, Critchley et al., 2002). Where there has been substantial and sustained fertilizer additions on former arable sites, this problem can be particularly acute and their ecological restoration requires a reduction in soil fertility in order to re-establish semi-natural communities (Marrs, 1993). Whilst recent research shows that recovery from added N can occur rapidly within 2-23 years of reducing N loads (Storkey et al., 2015), elevated residual P can pose a particular long-term problem (Marrs, 1993). The residual effect of elevated fertilizer P is often found, for example, in restoration schemes on former arable land, and in these situations some form of treatment is needed to reduce plant-available soil P concentrations for successful restoration. Various attempts have been made to determine a minimum target values for available P, and in such restoration schemes it is suggested that soil extractable concentrations should be <10 μg P g-1 for the re-establishment of high-quality, semi-natural grasslands (Walker et al., 2004).

Restoration ecologists have used a variety of strategies to reduce surface soil fertility in restoration schemes, including removal, leaching, sequestration (biological or chemical) or re-distribution through the profile (Marrs, 1993). The most usual approach is through some form of removal strategy where nutrients are depleted usually through continuous cropping - either as grain and straw or hay crops, although impacts often take years or even decades (Wells, 1980; Petgel, 1987). A more aggressive approach is to remove the topsoil which has been used extensively for heathland restoration in the Netherlands (Werger et al., 1985). With this topsoil removal strategy, there is a very large and sudden reduction in the total amounts of nutrients in the surface soil, but there may be problems with release of mineralizable N and soil acidification (Dorland et al., 2003).

An alternative approach suggested by Marrs (1993) was to use deep ploughing to either dilute the concentrated nutrients present in the surface layer with the infertile sub-surface soils, or burial, where the nutrients are made unavailable at least in the short-term. This burial approach has been pioneered in ecological improvement schemes within the U.K. by Landlife, an environmental charity (Landlife, 2008) Here, Full-Inversion Tillage (FIT) is used to transfer the surface soil underneath the sub-surface layer using a double-bladed plough. The aim is not to reduce the absolute amounts of nutrients on the site, rather to re-distribute them to where they should have a lesser impact on surface vegetation. There have been few assessments of the efficacy of the FIT approach, and where it has been tested, results have been equivocal with both positive (Glen et al., 2016) and negative reports on its performance (Czerwiński et al., 2015). Accordingly, here we test the use of the FIT plough on the change in soil chemical properties at two case-study sites with contrasting soil types, a sandy soil and a clay-loam.

One of the difficulties in assessing the effects of FIT on soil chemical properties is that data collected from sub-samples from a single soil-depth profile are inherently auto-correlated with depth and simple statistical analyses are inappropriate. For example, testing a range of properties using simple univariate statistical approaches, for example t-tests, can produce Type II errors if too many contrasts are made. We, therefore, suggest that multivariate analytical techniques can surmount these problems with one analysis incorporating all measured variables. Specifically, here we use Principal Response Curves (PRC), a method that can be used to determine significant treatment-induced effects on multivariate data along gradients against an experimental control; here soil chemical properties are compared down the depth gradient.

PRC is a direct gradient analysis based on a linear distribution model (van der Brink and ter Braak, 1999) that use partial redundancy analysis (pRDA) as the ordination method. To date, PRC has been exclusively used in the assessment of treatment effects on the structure of community matrices (plant cover or insect abundance) through time in repeated-measures experiments, i.e. across a temporal gradient (Moser et al., 2007; Alday et al., 2013). Here, we extend its use for testing the effects on soil chemical matrices down a soil-depth profile gradient after FIT has been used as the intervention treatment to reduce soil fertility. Our aim was to assess whether FIT applied at two case-study sites reduced surface soil chemical properties as expected and that the fertile surface soil was buried below the surface rooting zones.

## 2. Methods

### *2.1. Site descriptions*

Soil cores were collected from two sites possessing different soil types. The first site was an area of derelict former ex agricultural land of ca. 1 ha at the University of York, Heslington, Yorkshire, UK (-1.0416290o W longitude; 53.947242 o N latitude; British National Grid Reference SE 62999 50552). The site was in agricultural use up to 2011, after which it became ancillary land adjacent to a construction project at the University. During this period it had been used primarily for site access, storage of construction materials and had suffered heavy disturbance from the laying of service provisions (drainage and power services) associated with the construction. The site has a clay-loam soil, classified as Foggathorpe 2, a slowly-permeable, seasonally-waterlogged clayey and fine loamy-soil (Landis, 2016). The existing vegetation at this site was sparse with very few species, but pre-disturbance had been a *Lolium perenne* ley (MG7, Rodwell, 1992).The second site was an area of semi-suburban grassland of ca. 1.0 ha at Kirkby, Merseyside, UK (-2.876170 W longitude; 53.465736 N latitude; British National Grid Reference SJ 41702 96915). Presently, the site forms part of a Conservation Area, but historically was predominantly rural meadowland and *Salix* spp. plantation. The Kirkby site has a sandy soil, classified as Sollom 1 (Landis, 2016) with close to neutral pH, which typically is a deep, acid, sandy soil, with a bleached sub-surface horizon often affected by groundwater.

The approach used by Landlife in their environmental improvement after FIT is to sow a wildflower seed mixture; their aim being to produce a visually-attractive grassland vegetation (Glen et al., 2016). This approach does not produce native plant communities, but future improvements to their post-FIT treatment would be to introduce seed mixtures targeted at defined UK plant communities. At both sites, we suggest a species-rich MG5 *Cynosurus cristatus- Centaurea nigra* community (Rodwell, 1992) as an appropriate target vegetation community.

The FIT treatment was carried out on both sites by the same contractor using the same ploughing equipment (Danish Bovlund 64D plough). This plough uses a double ploughshare with mouldboards to invert the soil profile to a depth between 50 cm and 1 m. (Fig. S1), four times the overall depth of a standard agricultural plough (ca. 25 cm depth). Usually under FIT, this plough disturbs soil to about 70 cm depth (Landlife, 2008)

### *2.2. Soil sampling and analysis*

At both sites the soil-depth profile was sampled before inversion (no tillage - NT) and after Full-Inversion tillage (FIT); 42 days after FIT at Heslington and 23 days after FIT at Kirkby. The difference in timing was because of logistics of other operations on the sites; experience elsewhere suggests that any soil change effected by FIT would last for much longer than two months (Glen et al., 2015). On each sampling date, soil-depth cores were sampled from random locations; nine were sampled at Heslington and seven at Kirkby, the sampling density conformed to the recommendations for soil certification found in Stolbovoy et al., (2005). Each depth-core comprised eight sequentially-stacked sub-samples of 12 cm length, i.e. providing a sampled depth-profile of 96 cm, extending beyond the usual 70 cm of deep ploughing and well below the predicted soil inversion point (ca. 20-50 cm) (Landlife, 2008). Each soil sub-sample was placed into an air-tight plastic bag and transferred to a cold-store at the laboratory within three hours of collection. Soil pH, extractable P and NH4-N and NO3-N were measured on fresh soil which had been passed through a 2 mm mesh; total organic C and N and exchangeable cations were measured on air-dried soil passed through a 1 mm mesh.

Soil pH was measured in a 1:2 (w/v) soil/de-ionised water mixture using a Hanna Instruments 98103 pH meter (Hanna Instruments, Leighton Buzzard, UK). Soil extractable P concentration was measured using the NaHCO3 extraction method of Olsen et al., (1954) and both availableNO3-N and NH4-N concentrations were measured using the 2M KCl extraction method of Keeney and Nelson (1982); both followed by colorimetric determination. Exchangeable K, Mg and Ca concentrations were determined by emission/absorption spectrophotometry after extraction in a 1:10 mixture of soil: 1M ammonium acetate (pH 7.0) (Allen, 1989). To measure total C and N soil samples. were finely-ground in a roller mill; thereafter duplicated sub-samples (ca. 5 mg) were then desiccated and analyzed using a Carlo Erba NC2500 series CN Analyzer (Carlo Erba Instruments, Milan, Italy). Duplicate replicates that exceeded a coefficient of variation of 0.05 were re-analyzed.

### *2.3. Statistical analysis*

Principal Response Curves (PRCs) is special case of redundancy analysis (RDA) for multivariate responses in repeated observation designs (van den Brink and ter Braak, 1999), being specially designed to plot the compositional variation for applied treatments (factors) as deviations from an experimental control. Usually, PRCs are used to assess significant effects of applied treatments against an untreated control through time (e.g. van den Brink and ter Braak, 1999; Alday et al., 2013). The PRC is a RDA model where the main effect of time is ‘partialled out’, since the main interest in this analysis are the effects of treatment and there is less interest in the temporal change due to overall community development (Szöcs et al., 2015).

Here, PRC tested for a constrained effect of FIT on soil chemistry through the soil profile,i.e. the species-community matrices were replaced by soil chemistry matrices and the repeated-measures temporal gradient was replaced by the depth gradient through the soil profile. The soil chemistry matrices for each of the two sites were scaled and centred. The PRC analysis assesses the deviation in the soil chemistry through depth in response to FIT against the “control situation”, i.e., the soil before inversion (NT). A PRC diagram is then used to visualise these results, with soil depth constrained to the ordinate axis and the principal response (effect) of FIT is plotted as deviation from the control (NT) which is plotted as a vertical line at 0 on the x-axis. Included within the PRC plots are complementary soil chemistry weights, these weights represent the affinity of each soil chemical variable with the treatments analysed and the sign indicates the direction of the changes in effect (van der Brink and ter Braak, 1999), essentially indicating the most important soil variables contributing to the treatment response and their direction of impact. The explanatory power of the models and their goodness of fit were measured by calculating the variance explained (%) by the first canonical PRC axis and its corresponding eigenvalue (ƛ1), and the associated *F-*ratio and *p*-value determined for significance using Monte Carlo permutations and *F*-tests.

Testing for significant differences between the NT and FIT treatments at each depth strata was performed by applying a Williams Test (Williams, 1972) on the first principal component of a PCA at each sampling depth. All analyses were performed using ‘vegan’ version 2.0-2 (Oksanen et al., 2011) in the R statistical Environment (R Core Team, 2015).The data, meta-data and R-code for all analyses reported here are archived at

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## Results

For the Heslington site, the PRC model captured 26.4% of the total variance in soil chemistry, with depth and the depth x FIT interaction explaining 8.4% and 18.0% respectively (Fig. 1a); this model and the first canonical axis were both significant (P=0.002). FIT treatment differed significantly from NT only in the surface layer (0 cm to 12 cm depth); soils below 12 cm showed no significant differences between them. The surface soils (0-12 cm) showed positive weights for pH, C:N ratio and available concentrations of NO3-N, NH4-N, Ca and Mg, and negative weights for total C, N and available concentrations of P and K (Fig. 1a).

At Kirkby, the PRC model captured 54.8% of the total variance in soil chemistry; depth and the depth x FIT interaction explaining 25.0% and 29.8% respectively (Fig. 1b); this model and the first canonical axis were both significant (P<0.001). Soil chemistry after FIT treatment differed significantly from NT throughout the soil profile, except at depths of 30 cm and 54 cm (P *<*0.05 for all strata); throughout the profile all soil variables except for the available Ca concentration which increased after inversion (Fig. 1b).

There were, therefore, clear and highly significant effects detected by the PRC analysis. However, if the assessment of the surface soils had been performed using simple two-tail t-tests significant differences would have been found for all variables except soil pH at Kirkby and three variables (available P, K and Ca) at Heslington (Table 1). With twenty contrasts here, there is the potential to achieve significant differences by chance (Type II errors) and if a Bonferroni correction (Sokal and Rohlf, 1995) is used to mitigate this, three variables would not pass the adjusted threshold at Kirkby and none would pass at Heslington (Table 1).

Nevertheless, there were clear significant differences in response between sites produced byt the PRC ; at Heslington there were significant reductions in key soil variables in the surface layers (0-12 cm), whereas at Kirkby there was a large increase in the surface layer (0-36 cm) and a small effect in the deepest layers tested (>60 cm). One explanation for the different treatment effects between sites is the differences in the initial distribution of chemical properties with depth between the two sites. Essentially four different profile types were detected for individual elements, typical examples are illustrated in Fig. 2, and the four profile types were: Profile 1, high at the surface and a decline through the profile; Profile 2, low at the surface and increasing down the profile; Profile 3, highest at intermediate depths; and, Profile 4, no change with depth. For Heslington, total N and C, exchangeable K, extractable NH4-N, NO3-N and P showed profile 1 (Fig. 2), soil PH and exchangeable Ca showed profile 2, and C:N ratio and exchangeable Mg profile 4. At Kirkby, all but one soil variable exhibited Profile 3, the exception was soil pH with a profile 4. Essentially, the two sites had different starting profiles, Heslington showed ordered changes with depth for most variables whereas Kirkby showed mainly curvilinear responses with the greatest concentrations found at mid-depth; mixing these greater concentrations both upwards and downwards was almost certainly the reason for the differential effects of FIT between sites.

## Discussion

In this paper we have demonstrated the potential for PRC to assess changes brought about by FIT of soils in restoration schemes. The benefits to the use of this approach include (a) a rigorous statistical test of the effects of an intervention treatment relative to an untreated control, (b) a multivariate assessment that includes all measured variables and identifies those key variables changed by that intervention. We believe this approach has much to offer ecological restoration studies that involve assessment of impacts on soil depth profiles. In addition we demonstrated that FIT works for ecological restoration under appropriate circumstances, i.e. it can produce a topsoil of a reduced “fertility” which should assist in the restoration of species-rich plant communities of high conservation value.

### 4.1. *Benefits of using Principal Response Curves (PRC) in spoil depth studies*

One of the difficulties in comparing soil profiles is that the component parts of the profile are spatially-autocorrelated and this makes standard statistical approaches such as t-tests or analysis of variance invalid. PRC in contrast uses a direct gradient analysis based on a linear distribution model (van der Brink and ter Braak, 1999), effectively a regression approach based on a multivariate ordination, (partial redundancy analysis, pRDA). Crucially, PRC tests the effects of an intervention or interventions against an untreated control along a gradient. In most previous uses of PRC, community matrices of species abundance have been tested along a temporal gradient tested; examples of their use include ecotoxicology where the effects of a pesticide have been tested through time (van der Brink and ter Braak, 1999; Moser et al., 2007) or in vegetation science where species change has been assessed through time (Alday et al., 2013). There is no a priori reason why PRC cannot be used on other matrices or gradients, and here it has been shown to be successful in analyzing soil chemistry matrices down a soil-depth profile.

The benefits of this approach are many. First, it is a multivariate test and hence all appropriatevariables can be included, here we used a selection of soil variables but this could be extended to include other variables such as mineralization rates or microbial activity. PRCs were originally intended for use in formal replicated experimental designs, and its use here does not strictly conform to this as it is a structured survey, i.e., there is a treatment comparison (intervention versus control) down the soil profile gradient. An obvious further extension to this approach in ecological restoration would be its use for monitoring soil change through time; after the initial study where a baseline of change against the undisturbed profile has been created to test the strength of the intervention, there is no reason why temporal data could not be included in later analyses, effectively as additional “treatments”, to detect significant change through time (Fig. 3). Second, as a multivariate test, PRC tests for significance based on all data in a single analysis and precludes issues associated with multiple testing where there is the potential to accept significant differences derived entirely by chance (Type II errors). Here, we showed that at Heslington, when Type II errors were accounted for using Bonferroni correction, no significant difference were detected in the surface soil. Here, t-tests were only computed for the surface 12cm; inclusion of all depth layers would increase the number of potential Type II errors considerably.

4.2. *Use of FIT in ecological restoration*

It is generally accepted that there is a need for the establishment of infertile conditions for the restoration and maintenance of most semi-natural plant communities of high conservation value in northern Europe (Bakker, 1979, Marrs, 1993). This is especially true when attempting to restore such communities on ex-arable soils (Critchley et al., 2002; Walker et al., 2004) where there may be considerable elevated residual fertility (Marrs, 1993). Given this, it is surprising that there have been few attempts to document the use of FIT in ecological restoration schemes. Landlife, a charity with a mission which inter alia includespromoting new wildflower landscapes and creative conservation, has pioneered the use of FIT in a range of conservation schemes throughout the UK, but no attempt to date has been made to assess its efficacy. This paper represents the first statistically-rigorous assessment of FIT for ecological restoration.

With FIT, under ideal conditions, the soil profile is flipped or inverted with the surfacetopsoil being placed under what was the previous sub-soil. In most situations the starting surface topsoil would have a greater fertility than the subsoil and hence after FIT there should be an almost instant reduction in soil fertility suitable for the establishment of semi-natural plant communities of high conservation value. Here, this result was found for one of the two tests sites (Heslington) where after FIT there was a significant change in the soil properties of the surface 12 cm, and the soil extractable P was almost halved in concentration to a level below the 10 µg P g-1 threshold identified by Walker et al., (2004) as suitable for the maintenance of species-rich grassland. So for this site the results could be viewed as very positive. The reason why FIT was successful at Heslington was because most soil properties changed in an ordered way with soil depth, increased concentrations at the surface and lower values in the sub-soils; this was especially the case for the elements that are known to restrict the restoration of high-quality semi-natural ecosystems, especially P (Marrs, 1993).

The results for the Kirkby site were less successful in that there was an increase in most soil variables throughout the soil profile, which was particularly prominent at the soil surface after FIT. This can be explained with reference to the soil chemistry of the pre-treatment profile. In contrast to the Heslington site, where there was clear directional change in soil chemical variables with depth for most variables, at Kirkby the responses were mainly curvilinear with maximum concentrations in mid-profile. This profile distribution is probably a result of previous fertilization and substantive leaching through its sandy substrate. When this type of profile was inverted, some of the soil chemicals previously found in mid-profile were re-distributed mainly into the surface layers, effectively enhancing the fertility of the topsoil layer, but with some being transferred to deeper layers through mixing. In these situations FIT is not appropriate for ecological restoration purposes where the aim is to reduce surface soil fertility.

Thus, FIT has considerable potential in ecological restoration schemes where there is a management requirement to reduce surface soil fertility and the surface soils are more fertile than the sub-surface layers. At Heslington, FIT was shown to be capable of reducing soil available P and other variables in the surface 12cm here rapidly. FIT is relatively quick to implement as approximately 2-3 ha can be treated in one day (Landlife, 2008), although the exact area that can be treated will depend of soil type. However, given the results for Kirkby, it is suggested that a thorough investigation be carried out before treatment to ensure that the soil profile type is suitable for this treatment (here Heslington yes, but Kirkby no). Unfortunately, to date, assessments have not usually been implemented before FIT treatment in the UK. FIT was suggested as a possible method for ecological restoration of a large-scale project to restore acid grassland and heathland on ex-arable land at Minsmere in Suffolk, where the objective was to reduce surface soil pH, exchangeable Ca and extractable P concentrations (R. H. Marrs, pers. comm.). An intensive scoping study showed that, like Kirkby, FIT was deemed inappropriate because there was no significant change in any of these soil properties throughout the 1 m soil-depth profile tested (Marrs et al., 1998). Taken together, this evidence suggests that a pre-treatment scoping is essential before FIT is implemented for ecological restoration using the method similar to the one outlined here, i.e., a minimum of seven depth-profile cores per haas recommended by Stolbovoy et al. (2005). Although this may see a relatively few number of samples to reflect spatial variation, strict random selection at this level was sufficient here to detect significant changes in soil profile chemistry here. A greater number of samples will almost certainly improve the potential of this approach for detecting change with depth. In a similar vein, we have only tested the effects of FIT on two small case-study sites. Further work is needed to assess the generic use of FIT in a range of different ecological restoration scenarios on a range of soil types.

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Appendix A. Supplementary data

The following is Supplementary data to this article:

{Insert file name}

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**Table 1.**

Surface soil chemical properties (0-12 cm) in undisturbed (NT) and inverted profiles (FIT) at two contrasting sites, Heslington and Kirkby in the U.K; mean values (±SE) and t-values are presented for both sites. Significant differences (P<0.001) are dark-shaded; significant differences detected by individual univariate contrasts (P<0.05) but do not meet probability threshold after Bonferrroni correction (Sokal and Rohlf, 1995) to account for possible Type II errors for each site (P<0.005) are light-shaded.

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Soil variable | |  | Kirkby (=7) | | | |  | | Heslington (n=9) | | |
|  | NT | | | FIT | t | P | NT | FIT | | t | P |
| pH | 6.1±0.06 | | | 6.1±0.1 | 0.82 | >0.05 | 7.2±0.14 | 7.4±0.1 | | 1.40 | >0.05 |
| Total C (%) | 0.7±0.2 | | | 3.2±0.1 | 13.81 | <0.001 | 1.4±0.2 | 1.0±0.1 | | 1.96 | >0.05 |
| Total N (%) | 0.06±0.01 | | | 0.22±0.03 | 6.25 | <0.001 | 0.13±0.02 | 0.08±0.01 | | 2.99 | >0.05 |
| \*C:N | 11.6±1.01 | | | 15.3±1.34 | 2.55 | 0.027 | 11.0±0.52 | 12.5±0.8 | | 1.69 | >0.05 |
| Available P (μg P g-1) | 2.9±0.7 | | | 11.7±1.2 | 7.64 | <0.001 | 14.8±2.2 | 6.7±2.6 | | 2.73 | 0.015 |
| Available NH4 –N (μg N g-1) | 1.6±0.7 | | | 6.0±1.6 | 2.88 | 0.020 | 2.7±1.7 | 2.4±1.3 | | 0.15 | >0.05 |
| Available NO3-N (μg N g-1) | 1.3±0.6 | | | 7.7±1.1 | 6.10 | <0.001 | 2.3±0.6 | 2.3±0.4 | | 0.09 | >0.05 |
| Exchangeable K(μg K g-1) | 24.6±4.3 | | | 138.8±16.0 | 8.17 | <0.001 | 96.7±12.2 | 68.4±6.4 | | 2.33 | 0.037 |
| Exchangeable. Ca(μg Ca g-1) | 530±99 | | | 1708±75 | 11.22 | <0.001 | 1.8±0.17 | 2.8±0.4 | | 2.49 | 0.030 |
| Exchangeable Mg (μg Mg g-1) | 26.5±6.7 | | | 65.5±7.1 | 4.71 | <0.001 | 0.1±0.01 | 0.1±0.03 | | 0.46 | >0.05 |

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**Fig. 1.** Principal response curves analysis of changes in the soil chemistry down the profile comparing the effects of full inversion tillage (FIT) to an untreated control (NT) in two contrasting sites, (a) (Heslington,and (b) Kirkby) undergoing ecological restoration. Significant differences are denoted; \* = P<0.05;\*\*=P<0.01; \*\*\*=P<0.001. Note the vertical line at 0.0 on the x axis is the untreated (NT) treatment, the FIT is a deviation from this.

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**Fig. 2.** Illustrative examples of the four types of change in soil properties through the undisturbed soil depth profiles detected at the two test sites undergoing ecological restoration.

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**Fig. 3.** Hypothetical examples where the effects of FIT on soil chemical properties could be monitored through time against an untreated control (NT) using principal response curves: (a) Success, where a phase shift in the surface soils has been achieved that is stable through time, and (b) Failure, where the original soil is resilient and there is a return to the status quo through time. Arbitrary time periods (t0, tn, t2n) have been used for illustration.

**Appendix 1. Supplementary Materials**

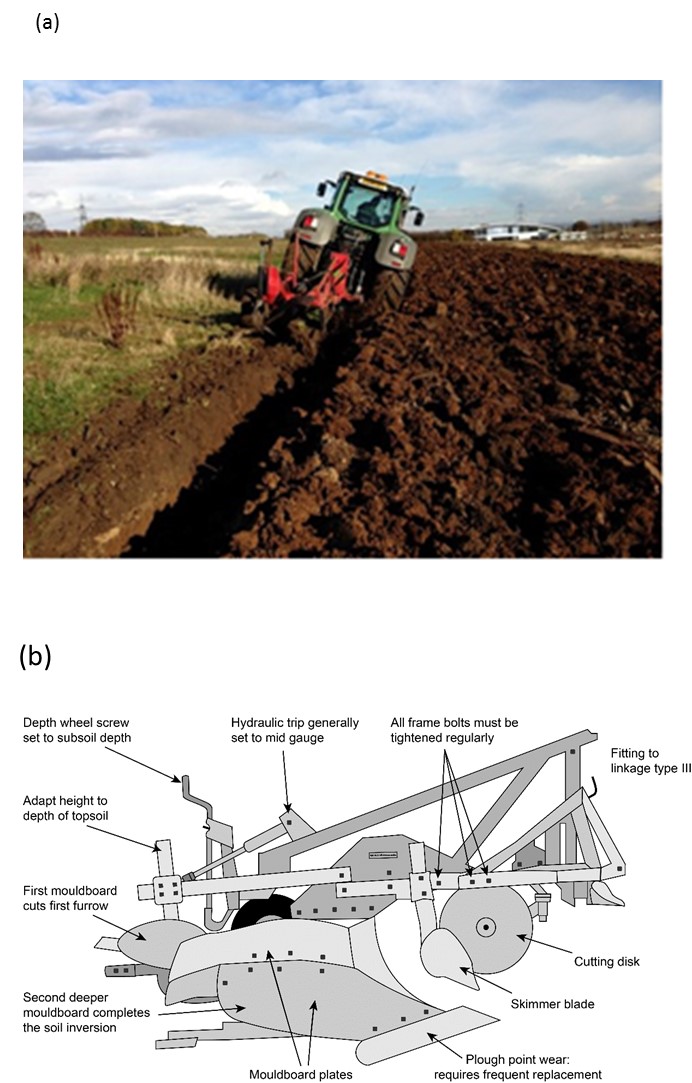


Fig.S1. (a) Photograph of the FIT plough in action (photo G. Milligan), and (b) schematic diagram of the FIT plough (from Landlife, 2008).