Trials to Identify Soil Cultivation Practices to Minimise the Impact on Archaeological Sites
(Defra project No: BD1705)

Effects of Arable Cultivation on Archaeology
(EH Project number 3874

Known collectively as: 'Trials'

Sid 5 Summary of Results

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Executive Summary

7. The executive summary must not exceed 2 sides in total of A4 and should be understandable to the intelligent non-scientist. It should cover the main objectives, methods and findings of the research, together with any other significant events and options for new work.

OA's work for Defra on the *Management of Archaeological Sites in Arable Landscapes* project (BD1701) (OA 2002), collated information defining the damaging ways in which archaeological sites are being affected by arable agriculture and outlined possible means of avoiding or reducing damage to the archaeological resource through reversion to grassland or adoption of more benign cultivation systems. It recommended that further work was needed to explore some of the key practical issues involved in minimising damage to the resource. Therefore, the 'Trials' project aimed to study these issues in detail.

The scientific objectives as stated in the project design (OA 2005) were to:

- Assess the effectiveness and viability of minimal cultivation, and differing soil management techniques, in preserving the archaeological resource and to compare these techniques with conventional arable/soil management systems.
- Combine the results of the above assessment with existing studies on related issues to understand the full implications of adopting these techniques both in terms of their effect on the archaeological resource and farm based agronomics.
- Recommend a series of agricultural and soil management options suitable for protecting archaeological sites covering a range of differing soils, topography and arable regimes.
- Develop cost-effective methods for monitoring the effectiveness of such techniques.

In order to address the research questions and objectives identified a series of experimental studies were established.

Studies were undertaken to look at sub-soil pressures resulting from tillage implements and vehicle loads and the effect these could have on archaeological artefacts. A series of experiments were carried out both in the soil bin laboratory at Cranfield and in the field to study the sub-surface pressures exerted at depth by a range of arable farming operations. These included, for example, cultivation, harvesting and spraying, transmitted via both tyres and rubber tracks. Replica ceramics and human bone were tested to destruction to determine a range of breakage thresholds which could then be directly related to the pressures exerted at depth by the arable procedures tested.

One of the key stumbling blocks to introducing non-inversion tillage agriculture is the perceived need for subsoiling to accompany these techniques to prevent the build up of pans and deep soil compaction. The project therefore also studied the relationship between tractor passes and soil compaction and degradation over an accelerated 30-year period. These trials and those to examine the effects of primary cultivation systems were carried out by laying out a series of specially constructed archaeological sites.

These were then subjected to up to the equivalent of 30 years of different cultivation techniques over a 3 period (Accelerated trials), and also in a separate trial, 3 years of cultivation operations over a 3 year period (Real time trials) for comparative purposes. The tillage treatments tested here were deep (0.20-0.25 m) and shallow (0.125 m) mouldboard ploughing, non-inversion tillage using a combination tillage tool (namely: Simba Solo) and direct drilling or zero tillage. The archaeological sites were constructed under a ploughsoil reinstated at 0.25-0.30 m depth. Experiments were also carried out which allowed a comparison of the effects of 0, 1, 2 and 5 passes of the subsoiler on these archaeological sites.

A series of earthworks were also constructed in the form of a ridge, four round barrows and a stretch of ridge and furrow and then subjected to direct drilling (20 accelerated years worth), and 30 accelerated years worth of non-inversion (Simba Solo) and mouldboard ploughing to assess the effects of these different cultivation systems on the earthworks.

A series of monitoring stations using glass, recycled coloured glass, sand and radio transponders were used to monitor depths of disturbance and soil movement to assess the best ways in which compliance with suggested management options could be monitored.

The key results showed that:
The lowest breakage threshold value recorded in the soil bin laboratory trials using replica historic pots (1.3 bar for a shell-tempered late Saxon ‘St Neots type’ cooking pot) and modern terracotta pots (1.1 bar), would have been exceeded by the pressure achieved below the ploughsoil by the drill, ‘Simba Solo’, sprayer, combine harvester, tractor and trailer and both shallow and deep mouldboard ploughs. Higher moisture content could account for up to a 0.25 bar increase in pressure transfer. Mouldboard ploughing caused more pressure transference below ground than non-inversion tillage techniques.

Both deep (0.20-0.25 m) and shallow mouldboard ploughing (0.125 m) led to the truncation of archaeological sites over time despite the reinstated plough soil being 0.25-0.30 m deep. Rates of archaeological truncation were recorded at:

- Accelerated deep mouldboard plough plots 0.10 m over 30 years - 0.003 m a year.
- Accelerated shallow mouldboard plough plots 0.07 m over 30 years - 0.002 m a year.
- Real time deep mouldboard plots 0.03 m over 3 years - 0.01 m a year (this faster rate may indicate an initial period of settling).
- Subsoiling caused considerable and sustained damage to the archaeological features.

These rates of attrition are similar to those seen on real archaeological sites where truncation has been recorded. Truncation of archaeological sites over time is likely to be caused by a combination of gradual long term truncation through the difficulties in maintaining an exact plough depth (especially if working at a restricted depth), soil movement created by the forward movement of the plough and more dramatic truncation through cultivation when moisture levels are high (above field capacity).

The study shows little development of compaction pans away from the wheelings in any of the plots including the direct drill and non-inversion tillage, even after 30 years of primary and secondary tillage providing there have been no random wheels over the soil. The evidence suggests that shallow subsoiling/deep tillage/loosening to 0.25 m deep will remove the effects of the surface soil damage caused by wheelings under a controlled traffic management system. This is unlikely to be a serious problem on many soils as earlier studies concluded that crop yields are unlikely to be significantly improved unless the crop is spring sown on a sandy soil in seasons with low rainfall. Both conventional and shallow ploughing operations are likely to reduce the natural soil strength and make soils more vulnerable to compaction than non-inversion techniques.

Both mouldboard ploughing and non-inversion tillage using a Simba Solo resulted in the destruction of earthworks. The average height loss of the non-inversion tilled earthworks is *c* 0.01-0.03 m per year, the variation correlating significantly with earthwork type. The average height loss of the ploughed earthworks is *c* 0.01 m per year, which is comparable with the few actual rates of truncation recorded in real earthworks, which average *c* 0.01-0.04 m per year. Non-tillage (direct drilling) was found to offer the only long-term sustainable protection for most earthworks if they remain in cultivation.

Based on these results a series of recommendations were made to prevent damage to archaeological sites in arable land. These included recommendations that inversion tillage (i.e. any form of mouldboard ploughing) should not be carried out on flat sites, nor inversion or non-inversion tillage (using Simba Solo type machinery) on earthworks. A series of recommendations have been made to ensure that pressure transference from agricultural machinery does not cause risk to archaeological sites and ways in which compaction over a field containing archaeological deposits can be avoided, including using controlled trafficking, keeping heavier loads off site and using wide section or dual tyres at SAFE lower inflation pressures commensurate with the load and duty cycle (or tracks) to minimise pressure transference.

Key to reducing risks from pressure and preventing the formation of compaction pans is avoidance of archaeological sites when moisture contents exceed field capacity. If the recommendations discussed in this document and Defra's Good Soil Management Code of Practice (2009) are adhered to then the formation of compaction pans will be minimised and therefore the need for subsoiling can be reduced significantly. In areas of the controlled traffic/wheelings where compaction is seen then shallow loosening can be applied to remove this, to a depth that does not exceed 0.30 m.

In the case of earthworks direct drilling and managed pasture are the only feasible options for sustainable protection. In the case of slopes neither deep nor shallow mouldboard ploughing should be undertaken. Whilst non-inversion tillage is damaging to earthworks due to its capacity to move and level irregularities, it can be used on slopes with the following caveats:

- Non-inversion tillage or indeed any tillage should not be undertaken on upper and middle slopes where the slope is more than 5 to 6 degrees (direct drilling may be possible but should be assessed on a case by case basis). This is especially relevant on predominately fine sand and silty soils where the risk of soil erosion is greatest. Soils with higher clay content may be cultivated but they would also need to be assessed on a case by case basis depending on the history of erosion and soil depth.
- Non-inversion tillage must be undertaken either along the contours of the slope or approximately perpendicular to the main field slope, and not up/down slope.
- Good slope tillage management should be adhered to i.e. tillage should be practised in one direction one year and the other direction the year after. This will compensate for any small movements of the soil.

All of the above recommendations support the principles of good soil management which help to sustain good agricultural practices by minimising compaction and promoting crop growth whilst attempting to preserve buried archaeological sites.

Both differently coloured glass and radio transponders proved effective in allowing depths of cultivation disturbance to be recognised. It is suggested that the two techniques would be best used in combination. Glass would be used to show the farmer that he was getting close to the archaeological deposits so that he could self-regulate. The transponders could then be used as a way of cross-checking compliance if buried just below the stated cultivation depth, but would need a number of stations inserted to ensure reliability.

This work provides practical measures which will now underpin policies of heritage protection, arising from developments in the Planning Policy Guidance and heritage legislation and allow informed management recommendations to be made. The results of this work will also be critical for those involved in providing management advice for archaeological sites in arable landscapes, including Natural England and English Heritage. It provides them with tried and tested recommendations based on actual results, rather than hearsay, which can be discussed with farmers and other land managers and implemented through agri-environment schemes.

Project Report to Defra

8. As a guide this report should be no longer than 20 sides of A4. This report is to provide Defra with details of the outputs of the research project for internal purposes; to meet the terms of the contract; and to allow Defra to publish details of the outputs to meet Environmental Information Regulation or Freedom of Information obligations. This short report to Defra does not preclude contractors from also seeking to publish a full, formal scientific report/paper in an appropriate scientific or other journal/publication. Indeed, Defra actively encourages such publications as part of the contract terms. The report to Defra should include:
    - the scientific objectives as set out in the contract;
    - the extent to which the objectives set out in the contract have been met;
    - details of methods used and the results obtained, including statistical analysis (if appropriate);
    - a discussion of the results and their reliability;
    - the main implications of the findings;
    - possible future work; and
    - any action resulting from the research (e.g. IP, Knowledge Transfer).

Introduction

Background

OA's work for Defra on the *Management of Archaeological Sites in Arable Landscapes* project (BD1701) (OA 2002), collated information defining the damaging ways in which archaeological sites are being affected by arable agriculture and outlined possible means of avoiding or reducing damage to the archaeological resource through reversion to grassland or adoption of more benign cultivation systems. It recommended that further work was needed to explore some of the key practical issues involved in minimising damage to the resource using these and other cultivation and soil management techniques. Therefore, the 'Trials' project aims to study these issues in detail. It aimed to determine the effects of differing agricultural and soil management techniques on archaeological remains and develop cost-effective methods for monitoring the impact of such techniques. The results of this work have been used to outline a set of cultivation and soil management recommendations on how farming systems can be adapted to reduce damage to archaeological sites.

In response to increasing concern about the damage caused to archaeological sites by agriculture, the Department of Culture, Media and Sport, in the Review of English Heritage legislation (2004), agreed that it would review the Class Consent for agriculture[1] and that English Heritage, in consultation with interested parties, would undertake the preparatory work to deliver this reform. As a result, in 2004-05 English Heritage and Defra funded the Conservation of Scheduled Monuments in Cultivation (COSMIC) project (OA 2005).

The COSMIC project developed, tested and delivered a robust and integrated risk assessment and mitigation model for archaeological sites in arable cultivation. The project also quantified the actual threat from arable cultivation to the monuments assessed in the East Midlands. For each site, the project devised a series of management and mitigation options that could be adopted to reduce the risk from cultivation, tested against farmer reactions. On the majority of fields containing scheduled and non-scheduled sites it concluded that it would be possible to continue cultivation operations, but to a restricted depth, to potentially provide sufficient protection to the archaeological resource. However, this judgement was based on the understanding that further research into how cultivation affects risk, and on effective ways to mitigate these affects, would be undertaken, this work forming the Trials project. Understanding the issue of cultivation damage, and being confident of the effectiveness of any management and mitigation measures put in place, is especially important now given the imminent abolition of Class Consent 1. Once this is abolished, effective management strategies to prevent further damage to scheduled sites can be developed, based on the sound evidence generated by the research undertaken here. This study therefore reflects the growing need for scientific research to underpin policies of heritage protection, arising from developments in the Planning Policy Guidance and heritage legislation.

Objectives

The scientific objectives as set out in the project design were, therefore, to:

- Assess the effectiveness and viability of minimal cultivation, and differing soil management techniques, in preserving the archaeological resource and to compare these techniques with conventional arable/soil management systems.
- Combine the results of the above assessment with existing studies on related issues to understand the full implications of adopting these techniques both in terms of their effect on the archaeological resource and farm based agronomics.
- Recommend a series of agricultural and soil management options suitable for protecting archaeological sites covering a range of differing soils, topography and arable regimes.
- Develop cost-effective methods for monitoring the effectiveness of such techniques.

Summary of Studies undertaken for Trials project

In order to address the research questions and objectives posed a series of experimental trials were set up. These are reported here and in detail in a series of stand-alone appendices with associated illustrations and include:

- 1 Sub-soil pressures resulting from tillage implements and vehicle loads (reported in detail in Appendix 1).
- 2 Buried artefact breakage laboratory trials (Appendix 2)

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[1] Class Consent 1 of the Ancient Monuments (Class Consents) Order 1994 allows ploughing to continue to a depth having already been reached in the preceding 6 years (on the understanding that this is unlikely to exceed 0.30m) as long as ploughing does not go deeper, and that no sub-soiling, drainage works, planting or uprooting of trees, hedges or shrubs, stripping of topsoil, tipping operations, or commercial cutting and removal of turf are carried out.

- 3 Pressure at depth in the field (Appendix 3)
- 4 Studying the effects of different cultivation systems on flat archaeological sites (Appendix 3)
- 5 Studying the effects of different cultivation systems on archaeological earthworks (Appendix 4)
- 6 Investigating practical methods to monitor disturbance depths (Appendix 3)

Section 7 (Appendix 5) lists a series of recommendations to prevent and/or minimise damage to archaeological sites from arable agriculture.

1 Sub-soil pressures resulting from tillage implements and vehicle loads

This part of the research formed an investigation into the pressures that a range of tillage implements and vehicle loads, transmitted via both tyres and rubber-tracks, exert on buried objects. This was conducted under strictly controlled, experimental conditions in the soil bin laboratory and a clay field at Cranfield University at Silsoe (reported in detail in Appendix 1). It is important to understand the effects of both tillage tools and their respective tractor sizes, together with harvesting and transport equipment, at depth in the soil, since the sub-soil pressures that these generate can cause damage to buried and vulnerable archaeological features and material.

Aims

The aims of this work were:

- to discover what pressures at depth would be caused by a range of tillage implements, at depths typical of those currently used in arable farming
- to discover what pressures at depth would be caused by a range of tyre and rubber track loads and tyre inflation pressures for tractors, harvesting machinery, trailers and trucks
- to compare the results from pressure studies carried out on both sandy loam and clay soils
- to develop a range of cultivation and appropriate soil management initiatives which will minimise damage to the archaeological evidence and which were taken forward into the Field Trial Studies (Sections 4 and 5)

Methodology

For the trials using the sandy loam, the study was conducted within the 20 m long × 1.7 m wide × 0.9 m deep soil bin (moisture content 9+/- 1%), where the required soil conditions could be easily replicated with accurate position control of buried artefacts, tyres and tillage tools and loads.

To determine the soil pressures, pressure transducers were installed into both flat plates and cylindrical vessels which simulate the tops of submerged rigid non-deformable walls and buried displaceable pots respectively. The plates were rigidly mounted to the floor of the soil bin, intended to represent a feature such as a wall foundation that is constrained vertically within the soil profile. The aluminium cylinder was chosen as a proxy for a ceramic or glass object, as aluminium has a similar modulus of elasticity to common ceramic/glass materials (Gordon 1991), whilst being more robust for experimental use. The cylinder represents a buried object, such as a pot or bottle that depending upon the relative pressure above and below the cylinder could be displaced downward within the soil profile.

The sensors were located in the subsoil of a Cottenham series sandy loam compacted with 6 passes of the soil bin processing roller to a dry bulk density of 1.60 +/- 0.10 g cm^3. A further 0.25 m of soil placed on top was compacted to 1.48+/- 0.08 g cm^3 to simulate a topsoil layer which, under arable conditions, will have been tilled to that depth within recent history, and will therefore have a dry bulk density lower than that of the subsoil. The sensors at depths of 0.25 m were replicated (3 times). This depth was selected as the shallowest practical position for the sensors, as in the field artefacts at a shallower depth would most probably have been physically damaged by previous tillage operations. Further plate and cylinder sensors were placed at depths of 0.25 to 0.50 m. Pressure sensor data were recorded for a range of tyre and rubber track loads and tyre inflation pressures on tractors, harvesting machinery, trailers and trucks and implements driven across the sensors. The investigation was conducted at a forward speed of 2 m/s (7km/h).

For the trials using clay, an Evesham series (formerly Wicken series (King 1969)) clay soil was used on the Cranfield University Farm at Silsoe. Here 12 cylinder-mounted sensors in 3 banks of 4 cylinders at depths of 0.30 m, 0.40 m, 0.50 m and 0.60 m were inserted into the clay by digging an access pit, augering 0.125 m diameter holes 0.50 m into the pit face, inserting the 0.10 m diameter cylinders an arm’s length along the hole and packing the free space above the cylinders with clay in a plastic state. The holes and the access pit were then backfilled and compacted to as near an original condition as possible. Since it was not possible to undertake individual passes of individual wheels/tyres on previously non-trafficked soil, as was done in the soil bin, a sequence of events was chosen where the load/pressure was increased with ascending levels of severity. These tests were conducted at a forward speed of 2m/s (7km/h).

Results

None of the implements tested in the soil bin exerted pressure at 0.25 m depth higher than 0.3 bar, with the press and heavy roller exerting the highest pressure and the drill and light discs exerting the lowest at less than 0.05 bar. The roll, chisel tine, plough, root share, a human, drill tines and light discs resulted in intermediate sub-soil pressures.

The tyre and track peak pressures recorded at 0.25 m are:

- A road tyre carrying 5 tonnes inflated to 7 bar pressure exerted a pressure of *c* 7.75 bar.
- A harvester carrying 10 tonnes inflated to 2 bar pressure exerted a pressure of *c* 2.75 bar.
- A rear tractor tyre carrying 2 tonnes inflated to 2 bar pressure exerted a pressure of *c* 2.5 bar.
- A harvester carrying 10 tonnes inflated to 1 bar pressure exerted a pressure of *c* 2 bar.
- A rear tractor tyre carrying 2 tonnes inflated to 1 bar pressure exerted a pressure of *c* 1.5 bar.
- A track carrying 12 tonnes exerted a pressure of *c* 1.25 bar.
- A harvester carrying 5 tonnes inflated to 2 bar exerted a pressure of *c* 1.15 bar.
- A set of dual tyres carrying 2 tonnes inflated to1 bar pressure exerted a pressure of *c* 1 bar.
- A harvester carrying 5 tonnes inflated to 1 bar exerted a pressure of *c* 0.75 bar.
- A track carrying 5 tonnes exerted a pressure of *c* 0.5 bar.

Other observations include the following:

- Studying the effects of multiple passes illustrates that the peak pressure tends to rise over those of the first pass by a small amount (*c* 10%) and then remain constant.
- The recorded pressure reduces significantly with depth. The pressure from the truck tyre with an inflation pressure of 7 bar is approximately 1 bar at a depth of 0.65 m; all other systems exhibit pressures less than 1 bar at depths of 0.40 m and deeper, falling to 0.5 bar and less at 0.65 m.
- A reduction in tyre inflation pressure and an increase in tyre size may reduce both the depth and severity of pressure transmission to buried objects. The use of dual tyres/wheels and rubber tracks has a very significant effect in reducing soil pressure at depth.

The information obtained from the clay field was limited as a result of the failure of some of the sensors. The other complicating factor is that the pressures recorded at 0.30 m depth are often the lowest rather than the highest in the vertical profile. This was attributed to shrinkage of the clay packing in the augured holes as a result of drying over the summer period, leaving the sensor without contact with the stronger (through drying) overlying soil.

However it is possible to arrive at some conclusions:

- The peak pressures generally reduce with depth, as shown for the laboratory data.
- The peak pressures generally increase with the severity of the expected loading, in that pressures under the human are between 0.00 and 0.01 bar, increasing to 0.04-0.08 bar under the terra tyre, up to 0.09 bar under the single tractor tyre, to 0.16-0.38 bar under the Fendt tractor + raised subsoiler and up to 0.44 bar below the MF390 tractor pulling the trailer.
- The values at 0.40 to 0.50 m deep are marginally less than those in the sandy soil in the laboratory study. This would be expected as the field soil was “virtually undisturbed” clay which would have greater strength than the laboratory sandy loam soil which was disturbed and re-compacted for each test.

Validity of results

It is unfortunate that the shallower sensors failed in the clay field experiment but it is interesting to note that the deeper sensors in this relatively undisturbed soil reported pressure that were marginally less than those in the disturbed sandy loam soil in the laboratory. Hence, the laboratory results can be considered a worst case scenario and using them for further analysis would give an extra margin of safety in any recommendations.

Conclusions

The evidence presented demonstrates that the effect of tillage implements on pressure transmission to buried objects is very small in comparison to that of the tyres/wheels of trucks, tractors, trailers and harvesters which were found to be approximate two orders of magnitude greater. The truck tyre loaded to 5 t and inflated to 7 bar is the most damaging of all the applied loads. This is followed at less than half the subsoil pressure by a combine harvester tyre loaded to 10 t but inflated to 2 bar; a further reduction in tyre pressure to 1 bar produces a still further (26%) reduction in subsoil pressure. This and other comparisons with the same load at 2 pressures illustrate the importance of reducing tyre pressure to the lowest SAFE working inflation pressure commensurate with vehicle stability and not inflicting damage to the tyre carcass.

It is evident from the work that an increase in tyre size and corresponding reduction in tyre inflation pressure reduces both the depth and severity of pressure transmission to buried objects through the soil profile. It is pressure rather than axle loads that has the primary effect. There are very important benefits from keeping the load per tyre to a minimum by using dual tyres or multi axles. The use of rubber tracks as an alternative to tyres will reduce the soil pressure under heavily loaded vehicles by a factor of two at a depth of 0.25 m.

The pressure transmission to buried objects from wheel and track loads is marginally less in clay soil than in sandy soils at depths of greater than 0.40 m. This is ascribed to the potentially greater strength of the undisturbed clay soil.

The above data enable identification of those operations where archaeological damage could occur, once the threshold values have been identified in later Sections 2 and 3.

2 Buried artefact breakage laboratory trials

Aims

The focus of this portion of the study was on the direct damage caused by pressure transfer to buried ceramic artefacts and human bone. The investigation was conducted to discover the potential effects of farming tyre/track operations on buried ceramic pseudo-artefacts and aged non-stratified, non-collagenous, human bone. These threshold peak subsurface pressures were then correlated to peak subsurface pressures collected in the laboratory (see above - section 1) and under field operations (see below - section 3), making it possible to define which field operations might or might not break buried artefacts in a cultivated field. The details of this work can be found in Appendices 2, 2A and 2B.

Methodology

This investigation used 4 types of replica ceramic pots to simulate real ceramic artefacts and medieval human bone. These pots were crafted for the project by Andrew McDonald, a Lincolnshire specialist in pottery reproductions. The key characteristics of each pot can be summarised:

- shell-tempered plot - wheel thrown, fired 900 degrees C - representing late Saxon
- grog-tempered pot - hand made, fired 700 degrees C - representing early Bronze Age beaker
- flint-tempered pot - hand made, fired 800 degrees C - representing middle to late Bronze Age to the Iron Age
- sand-tempered pot - wheel thrown, fired 900 degrees C - representing late Iron Age/Romano-British
- modern ceramic flower pots were also used

Aged, non-collagenous, medieval, human radii were used. These were unstratified finds from Wharram Percy medieval village, donated to the project by English Heritage (Simon Mays, Human Skeletal Biologist).

Ceramic strain gauge pressure transducers were used for the subsurface pressure sensing aspect of this work. The ceramic membrane pressure sensors (0.019 m diameter, 10 bar limit) were mounted into an aluminium cylinder 0.20 m long and 0.07 m in diameter. Before the tyre loads were applied in the soil bin laboratory studies, the sensors were randomly buried along the central axis of the soil bin (alongside the buried pots and bones) under 0.25 m of soil. The pots were instrumented with an electrical system that would enable *in situ* (buried) breakage detection (Dain-Owens 2006). The conductive circuit was connected via wires running from the buried pot to a circuit board, to a computerised data logging system, which recorded when the circuit broke. The data logger therefore allowed the time of object breakage to be determined and recorded while the object remained buried. The output from the buried pressure sensor was also recorded simultaneously.

The methodology used for the instrumentation and orientation of the pots was developed in a pilot project which trialed the methodology on replicates of modern flower pots buried at different angles within a small soil bin (Dain-Owens 2006 and Appendix 2). The weakest pots were found to be those placed horizontally within the soil and it was this, most vulnerable orientation that was taken forward to the main experiment. The pots were buried in the horizontal position (on their side) with their vertical axis positioned perpendicularly to the tyre's path of movement at a topmost depth of 0.25 m. The soil around and above the pot was at a similar bulk density to the rest of the soil in the soil bin (1.4 g/cm^3 surface to 0.25 m deep; 1.6 g/cm^3 deeper than 0.25 m).

The bones were all old enough to have lost the collagen inherent to any live and recently live bone and so had no elastic material strength properties. Each bone was buried dorsal-side-up, as if it was connected to a human arm positioned palm-down on the flat soil surface. The bones were buried both perpendicular and parallel to the oncoming tyre. The instrumentation for the bones was similar to that of the pots, two conductive trace circuits were created, one on the top side and one on the bottom side of the bone.

Once the bin was set up for each trial, the tyre was prepared for each run by inflating it to a specific pressure and loading it hydraulically to a specific load. Six runs were performed within each trial, with increasing inflation pressure and magnitude of load to increase overall surface loading at the soil surface. This generated successively higher subsurface pressures on the buried objects. Once the tyre passes were completed for each trial, the pots, bones, and sensors were excavated and all aspects recorded.

Results

Experiments with modern terracotta pots buried at 0.25 m at different orientations showed that the lowest breaking peak subsurface pressures were:

- 1.1 bar for horizontally-orientated pots
- 1.9 bar for 45-degree-orientated pots
- 2.2 bar for vertically-orientated pots

The replica pots broke as follows:

- the shell-tempered pot was the weakest, failing at 1.3 bar
- the grog-tempered pot is second-weakest, failing at 1.6 bar
- the flint-tempered pot is the third-weakest, failing at 3.1 bar
- the sand-tempered pot is the strongest, failing at 3.6 bar

The rims of all pots failed at slightly lower pressures than their bodies. An analysis of the breakage patterns of the pots was carried out and is reported in detail in Appendix 2B. The breakage dynamics of the bones showed that the perpendicularly-orientated bones broke primarily in tension. None of the parallel-orientated bones broke in this study, while most of the perpendicularly-orientated bones did break. The lowest peak subsurface pressure at which the bone broke was 2.8 bar. It is expected that smaller, less robust bones and vulnerable pieces such as skulls would break at lower pressures.

Validity of Results

Neither the replica pots nor human bones used in this study can reflect all artefact characteristics and breakage patterns. They do, however, together with the tests on modern ceramic pottery discussed in Appendix 2A, suggest a range of pressures over which a typical artefact assemblage may break. This allows a meaningful comparison with pressures exerted below ground by agricultural implements and tyres discussed above (Section 1) and below (Section 3) and allow discussions on mitigating this risk in the Recommendations (Section 7) below.

Conclusions

The determinative result extracted from the pot breakage data in the study on the replica pots was the lowest breakage point of 1.3 bar (1.1 bar for modern, more brittle pots) and 2.8 bar for bone. This provides a reference point to pot breakage indicating the ‘worst case scenario’ for the most fragile pots.

3 Pressure at depth in the field

Aims

The aim of this part of the study was to see if the results in Section 1 reflected real life conditions or whether the variable conditions found in the field would modify conclusions based on the soil bin studies. If this was not the case, any further investigations into these issues could be carried out solely in the soil bin. The additional data also allow an overall analysis of the issues of pressure at depth and artefact breakage in real field conditions building on the work done in the laboratory reported in Sections 1 and 2.

Methodology

The field trials involved examination of the effects of 4 different primary cultivation techniques and subsequent secondary cultivation activities on a series of specially constructed archaeological sites (Section 4). As part of this process a series of pressure sensors were buried within each of the areas used for the different types of primary cultivation to measure the pressures of all the implements/tyres at depth. Within each plot subject to the different tillage techniques three 10 bar ceramic strain gauge pressure transducers, mounted into aluminium cylinders as described previously, were buried under 0.30 m of soil positioned so that the centre of the wheel could pass directly over them in a straight line. Each plot was subjected to an annual cycle of loading operations from primary cultivation, drilling, rolling, spraying (twice), combine harvesting and a tractor and trailer. This was conducted within a 30 year accelerated time frame, clustered as separate sets of five-year cultivations, and was repeated with at least a month and sometimes up to 6 months between the five-year sets of field operations.

Results

Results from the accelerated field trials show that for all secondary operations following and including the primary tillage (considering all years and secondary operations) a difference in subsurface pressure was recorded. Deep inversion produces the highest pressures (*c* 2.05 bar) followed by shallow inversion (*c* 1.25 bar) then non inversion (*c* 1.15 bar) and finally zero/no-till till (*c* 1.1 bar). It is clear that although there are differences between the zero till and deep inversion the magnitude of the difference is minimal (only a mean 0.2 bar). Therefore in terms of field operations it is likely that other factors will have greater effects.

The mean subsurface pressure data averaged over all plots and all operations grouped into their respective 5 year intervals show that there is overall little effect of time (ie number of “year” repeats) on the resulting subsurface pressures. There is, however, a significant difference in pressure transfer (of approximately 0.25 bar) in lower and higher soil moisture conditions, which suggests that the moisture content at the time of field loading and pressure transfer is key.

Correlating the pot breakage threshold from the laboratory study (Section 2) to the fieldwork involved plotting the lowest peak subsurface pressure that broke pots (1.3 bar for the weakest, shell-tempered late Saxon type cooking pots) and comparing this with the results of the fieldwork. This allowed the ‘worst case scenario’ of pot breakage to be viewed relative to typical subsurface pressures from field operations.

The data show that these pressures were:
- “Zero” or “No-till” tillage operation does not produce any sub surface pressure and hence no artefact damage
- ‘Pigtail” tines and ‘zigzag’ harrows with a tractor on low ground pressure (LGP) tyres - *c* 0.50 bar
- ‘Cambridge Rolls’ with a tractor on LPG tyres - *c* 0.70 bar
- ‘Drill’ with a larger tractor with conventional tyres and inflation pressures - *c* 1.00 bar
- ‘Simba Solo’ with a heavy tractor on conventional tyres or tracks - *c* 1.25 bar
- Spray 1 and spray 2’ used a Spra-Coupe sprayer with a full tank of water - *c* 1.30 bar
- Harvester operation used a ‘pseudo’ harvester (a heavy tracked tractor), and a Lexicon 580 Claas combine harvester - *c* 1.30 bar. The tracks were used here to minimise the pressure at depth
- Tractor and trailer operation - *c* 1.50 bar
- Shallow plough, 0.125 m deep - *c* 1.60 bar
- Deep plough, 0.25 m deep - *c* 2.05 bar (in both these ploughing operations, the wheel of the tractor was driven in the furrow).

Validity of Results

Comparisons between the laboratory results and the accelerated field data show there to be good agreement between comparable treatments in both sets of trials. The fact that the field pressures were marginally lower can be explained by the fact that the laboratory data were recorded at a depth of 0.25 m and the field data at 0.30 m (to avoid any direct hit by tillage equipment). This helps to give confidence on the reliability of both data sets. All the treatments which were approximately comparable in each of the studies have yielded similar results. The transmitted pressures recorded in the accelerated field trials show little effect of “time” and are similar to those from the laboratory studies. This therefore suggests that further experiments in these areas could be carried out efficiently in the laboratory.

Conclusions

The data for subsoil pressures applied to buried archaeological artefacts in the field trials show that for primary tillage with secondary tillage operations, deep inversion produces the greatest values. However in terms of the overall effect of field operations on archaeological remains the significance of these differences is minimal; other factors result in much more significant impacts. Higher moisture content could account for up to a 0.25 bar increase in pressure transfer. This suggests that the moisture content at the time of field loading and pressure transfer needs to be considered when making management decisions. Higher soil moisture content weakens the soil structure, allowing greater wheel sinkage and hence pressure transmission.

The lowest breakage threshold value recorded in the soil bin trials using the replica historic pots, 1.3 bar for the shell-tempered late Saxon St Neots type cooking pots, would have been exceeded by the pressure achieved below the plough soil by the drill, Simba Solo, sprayer, combine harvester, tractor and trailer and both shallow and deep mouldboard ploughs. The modern terracotta pots buried horizontally (broken at 1.1 bar) would also have been broken by these operations.

4 The effects of different cultivation systems on flat archaeological sites

Introduction

The arable processes that cause damage to archaeological sites are well attested (for full details see OA 2002). Those that are examined here include:
- The erosive effect of repetitive primary cultivation, nominally "to the same depth"
- Deeper than previous cultivation practices related to the introduction of certain crops or undertaken to address problems with soil structure and drainage resulting from compaction

- Damage to artefacts and deposits through compression, deformation, pressure and through loss of soil structure

The field trials were designed to examine whether direct drilling, different forms of reduced tillage, and other suggested management options offered effective alternatives to reversion to grassland management by providing sustainable protection to the archaeological resource (reported in detail in Appendix 3). One of the key stumbling blocks to introducing non-inversion tillage agriculture is the perceived need for subsoiling to accompany these techniques to prevent the build up of pans etc. The project therefore also studies the relationship between tractor passes and soil compaction and degradation over an accelerated 30-year period.

Aims

The aims of this research were therefore to:

- Assess the effectiveness and viability of differing soil management techniques in preserving the archaeological resource and to compare these techniques with conventional arable/soil management systems.
- Use this information to recommend a series of agricultural and soil management options suitable for protecting archaeological sites covering a range of differing soils, farm agronomic practices, topography and arable regimes (Section 7).

As part of this the following issues were also considered:

- Compaction issues and necessity for remediation
- Relationship between soil moisture content and affects on below ground remains
- Relationships between compaction, tillage erosion and soil loss leading to effective deepening of cultivation
- Loss of soil structure and carbon content

Methodology

The field sites were divided between an area set up for an accelerated series of cultivations (accelerated site), where the equivalent of 30 years of agricultural processes were carried out in a three year period, and an area where the same processes were undertaken three times over the three year period of the field tests (real time trials). Each of the two field trial sites was divided up into four experimental plots (10 m x 20 m), each of which was subject to a different type of primary cultivation; mouldboard plough, shallow mouldboard plough, non-inversion tillage and direct drill. Following primary cultivation, implements representing the other field operations which would occur during a year were then run across the plots, all operating in the same “tramlines” or wheel marks.

Within each of the experimental plots six replica ‘archaeological sites’, each 2 m x 2 m in size, were constructed in the soil layer just below conventional ploughing depth. The soil cover over these ‘archaeological sites’ was reinstated at *c* 0.25-0.30 m. In total 48 replica archaeological sites were created, each with its own replica wall foundation, four postholes and a linear ditch. All the archaeological sites lay at a depth of 0.25-0.30 m below the ground surface, and all the archaeological features were cut down from this depth.

The base of the ditches and postholes were filled to a depth of *c* 0.15 m with a mixture of white desert sand and white stone to represent the important, lower primary and secondary fills of a ditch. The 0.10 m of upper fill consisted of white sand without the stones. This ensured that the depth of any disturbance to these features could be recognised during cultivation. On completion, each archaeological site was photographed and planned with a series of levels taken using a dumpy level across the plot, the features and the top of the ploughsoil.

A series of monitoring stations were also inserted into the four experimental plots. Damage warning and actual damage to the plots were investigated using indicator pits of sand, recycled glass chips and radio transponders. These were designed to indicate when the tillage disturbance had reached a certain depth. The glass chips and sand were placed in pits, 1 m or 0.5 m square or a shovel width, at differing depths, in layers 0.05 m thick in order to assess their suitability as a visual indicator of plough disturbance and potential archaeological damage. Each pit had a 0.085 m or 0.120 m transponder planted at its base to act as locator beacon. In Plots 1 and 2 (mouldboard plough and shallow plough) green glass was placed just above the archaeological horizon (0.20-0.25 m) as a visual warning of damage and blue glass was placed at the same level as the archaeological horizon, 0.25-0.30 m below the surface, to act as confirmation that damage was actually occurring. Within Plots 3 and 4 the green glass (warning) was placed within normal primary cultivation depth for each type of primary cultivation (0.05-0.10 m) and the second layer of glass (actual damage) was placed at the level of the archaeological layer (0.25-0.30 m) for all. Different sand representing the depths of fill within the archaeological features was also used to identify depths of disturbance.

Radio transponders were also used to record disturbance. The transponders within the mouldboard plough plot were placed at a depth of *c* 0.20-0.25 m and in the shallow plough plot the depth was set at *c* 0.125 m. Within the other two plots the depths were set at the respective primary cultivation depths, i.e. for the minimum tillage plot at *c* 0.10-0.15 m and for the direct drill plot at *c* 0.05–0.10 m. A transponder reader was developed which could record the serial number of each transponder, allowing this to be logged straight onto a mobile computer with touch screen controls so that movement of the transponders could be logged.

Monitoring took place throughout the phases of cultivation to plot the emergence of glass and sand, the different percentages of each glass colour and any movement of the transponders. Following each simulated 5 year interval (for the accelerated trials) and after every pass (for the real time trials) penetration resistance was recorded using an Eijkelkamp Penetrologger on both wheeled and unwheeled areas to see if compaction pans had built up, and at what depth. Any visible evidence for soil deformation and deterioration, such as rutting, smeared surfaces, water ponding and loss of granular structure was recorded and the moisture content of soil was recorded every simulated year. Soil erosion was recorded through contour survey undertaken before and after field trials. Samples were also taken for carbon and bulk density analysis at the end of all cultivations to examine the effects of 30 years worth of accelerated cultivation.

The cultivation sequence started with the primary cultivation, mouldboard plough (0.25 m depth), shallow plough 0.125 m depth), non-inversion tillage - Simba Solo (0.125-0.20 m depth) and direct drill (0.075 m) followed by the subsidiary operations (secondary cultivations), including roll, sprayer, combine harvester and tractor and trailer combination. Any evidence of wheelings which had developed as a result of the secondary cultivations was removed using a set of chains and/or zigzag harrows prior to the next stage of primary cultivation. A subsoiling strategy was developed which allowed comparison between the effects of no subsoiling, 1, 2 and 5 passes of the subsoiler. The subsoiler was set at a depth of 0.40 m.

Once all cultivation had finished the archaeological sites were archaeologically excavated. Any changes from their original layout were recorded on an overlay plan. Levels were taken (using a dumpy level) on the tops of the features, the top of the subsoil and the cultivation soil, and photographs were taken. Any localised changes within the archaeological sites caused by cultivation or by compaction were recorded. A section was drawn across each plot showing the cultivation soil, overburden and ditch. Half sections of the postholes were also recorded where these were affected by cultivation. The glass and sand pits were also excavated and the final transponder locations recorded.

Results

During cultivation fresh damage was easy to distinguish on the surface of the soil as the glass and sand from the monitoring stations were brought up as coherent deposits, clearly visible on the surface. When this material was subject to further cultivation the coherent deposits rapidly disappeared, becoming dispersed and, in the case of the sand, reabsorbed back into the soil.

Accelerated mouldboard plough - key results:

- At Year 1 indicator stations showed warnings of damage (originally buried at 0.20-0.25 m - ie at plough depth)
- At Year 2 actual damage (0.25-0.30 m) was recorded from 2 indicator stations and 2 archaeological plots. The level of damage gradually increased up to Year 5
- In Year 6 a large increase in damage was seen as a result of higher moisture contents (26%). All 6 plots showed damage. Ruts *c* 0.10-0.20 m caused by secondary cultivation equipment had to be removed by a zig zag harrow prior to further primary cultivation
- Damage continued at a reduced level until the wetter Years 21-30. This gradually increased with the secondary ditch fills and large amounts of sandstone appearing on the surface by Year 25, showing that cultivation was reaching depths of 0.35-0.40 m having removed the top 0.10 m of the fills of these ditches. This increased damage again reflected an increase in moisture levels (to 21-22%)
- Disturbance of all the transponder stations was seen during Year 5

Post-cultivation excavation of the plots showed that:

- All the plots were affected by compaction under the wheeling at depths of between 0.08 m and 0.12 m
- No distinct compaction pans were seen in the rest of the plough soil
- The 30 years worth of mouldboard ploughing caused significant truncation to the archaeological features. The ditches, postholes and subsoil had been eroded by between 0.07 m and 0.17 m across the six archaeological sites, which showed an average level of truncation of 0.10 m
- In the plots subsoiled only once there was very little direct indication of the damage caused as most of the evidence had been ploughed away consequent upon the deepening of the plough horizon. Scarring of the archaeological features was evident in the plots subject to multiple subsoiling operations, with scars clearly running through what was left of the ditch and postholes, although only the deepest level of disturbance could be seen in plan or section as only the lowest part of these fills survived. Very few stones from the upper layer of the walls remained *in situ* - most having been completely removed from the plots

Accelerated shallow plough - key results:

- The first sign of disturbance to the indicator stations did not appear until Year 2 when 1 warning of damage was seen (showing that in localised areas ploughing, despite being set at 0.125 m, had reached 0.20-0.25 m). By Year 5, 3 warnings of damage was seen
- In Years 6-8 damage increased dramatically, reflecting the higher moisture levels in these years. Archaeological damage was seen in 4 sites showing disturbance at depths of 0.25-0.30 m
- In Year 10, with lower moisture levels, 4 sites and one indicator station were still showing damage (at a depth of 0.25-0.30 m)
- After a reduction in the rate of disturbance, as in the mouldboard plough plots, there was a gradual increase in damage from Year 18. By Year 30, 5 archaeological plots and 3 indicator stations were showing actual damage
- In the shallow plough plot the acceleration in damage in the last 5 years of the trials was less noticeable than in the mouldboard plough plots. The extent of damage rose slowly from Years 18-25 onwards, reflecting the wetter conditions in years 21-25 (22%) and 21% in Years 26-30. Year 30 showed the biggest single rise
- All of the indicator stations showed actual damage at some point during the 30 year period
- On excavation the levels of truncation in the shallow plough plot ranged from 0.03-0.12 m, with an average across the six archaeological sites of 0.07 m, with rutting and compaction seen below the ruts to a maximum depth of *c* 0.20 m (the average was less than 0.10 m)

Accelerated non-inversion tillage - key results

- The Simba Solo brought up some of the upper layer of glass and sand (buried at 0.05-0.10 m below the surface) in Year 1 and in Years 20 and 30 the subsoiler brought up material from depths of 0.25-0.30 m
- By Years 25 and 30 all the transponder stations showed disturbance with a maximum movement of 2 m recorded. Whilst the transponders in this instance did not show consistent movement in the different stations, between them they did indicate disturbance over time
- In the majority of plots little rutting was seen on the surface and no compacted layers were identified below the wheelings or elsewhere

Accelerated field trials - direct drill - key results:

- The direct drill brought up some of the upper layer of glass and sand (buried at 0.05-0.10 m below the surface) in Year 1 and in Year 30 the subsoiler brought up material from depths of 0.25-0.30 m
- The subsoiler caused physical damage to the features, but was less damaging here than in the other plots

Real Time Mouldboard plough plots - key results:

- In Year 1, 3 warnings of damage were seen (at 0.20-0.25 m)
- Year 2 showed a significant increase in damage. Five of the 6 indicator stations showed actual damage and 4 of the archaeological plots showed archaeological damage (at 0.25-0.30 m in both cases). This coincided with the wetter year where moisture content was 26% and when ruts also formed
- Year 3, a dryer year, also showed the same 4 archaeological plots and 5 indicator stations affected
- One of the transponder stations showed movement in the first year of cultivation, which increased to all in Years 2 and 3. The maximum distance travelled was 2.50 m
- The majority of damage to the archaeological plots was caused by the subsoiler. However, across all the plots a thin layer of subsoil and the upper layers of the archaeological features had been truncated. The depth of disturbance across the 6 archaeological sites ranged from 0.01-0.05 m, with an average depth of 0.03 m
- The ploughsoils ranged in depth from 0.26 m to 0.32 m, quite closely reflecting their original depths
- No ruts caused by wheelings were identified or elsewhere and no evidence survived of the rutting seen in Year 2
- Where the plots were subsoiled the scars could be clearly seen both running through the ditch and truncating the postholes. Subsoil adjacent to these features had been dragged into the features to depths of 0.12 m. Subsoiling the plots twice effectively doubled the amount of damage caused and was beginning to compromise the visibility of some of the postholes
- The sandstone blocks from the wall had been moved by the subsoiler only, clearly illustrating its destructive powers. In some cases the blocks were removed entirely from the plot, in others they were scattered throughout the soil sequence, with some raised in the ploughsoil only *c* 0.08 m below the surface. Significant subsoiler scarring could also be seen on the lower levels of stones at a depth of 0.33 m below ground level

Real Time Shallow plough - key results:

- A warning of damage was seen in one of the indicator stations in Year 1, at 2 in Year 2 and at 3 in Year 3 showing a gradual increase in the frequency of disturbance at this depth. This indicates that shallow ploughing at 0.125 m was extending to 0.20-0.25 m, the depth of the warning layer. There is no indication that cultivation reached the level of the archaeological features, either from the indicator stations or from the features themselves.
- One transponder station showed evidence of disturbance during the first year of cultivation, increasing to 3 in Year 2 and 4 in Year 3, an increase mirroring the disturbance of the glass

- Excavation of the monitoring pits showed small areas of the upper, warning layer disturbed by the plough. Some of the sections from the excavated monitoring pits showed that vertical blocks of the glass/sand layers were displaced and dragged into the adjacent soil in the direction of movement of the subsoiler
- No evidence for rutting or compaction was seen

Real Time non-inversion - key results:
- The only material brought to the surface from the monitoring pits was seen after the first pass of the Simba Solo which brought up some of the upper layer from 3 stations
- Transponder disturbance increased from one station in Year 1, to 2 in Year 2 and 3 in Year 3.
- Damage to the plots occurred only as result of subsoiling as above
- There was no visual evidence for rutting or compaction pans on any of the plots

Real Time direct drill - key results:
- As above but with disturbance seen from the upper layer of 4 indicator stations. All transponder stations were disturbed by Year 3, although movement was minimal

Comparison between accelerated and real time plots

One of the main reasons that the real time trials were undertaken was for comparative purposes, to enable an assessment of the accuracy and the representativeness of the accelerated trial results to be made. Comparison between actual years (ie Year 3 accelerated and Year 3 real time), and those between ‘equivalent time’ when they were both cultivated (eg between Year 2 Real Time (RT) and 6 Accelerated (A)) showed that it was more appropriate to compare the results when the number of passes are similar (actual years), unless a more critical factor comes into play, such as a significant change in moisture level. Leaving aside Year 2RT, when this more dominant critical factor was effective, the results of Years 1 and 3 are reasonably comparable between the two trial sites, despite the accelerated nature of the trials.

Comparison of rates of damage between accelerated and real time plots

Overall the average rate of truncation of the archaeological features was:
- Accelerated mouldboard plough plots 0.10 m over 30 years - 0.003 m a year
- Accelerated shallow plough plots 0.07 m over 30 years - 0.002 m a year
- Real time mouldboard plots 0.03 m over 3 years - 0.01 m a year

On the face of it the rate of truncation in the real time plots is higher than in the accelerated plots. This is likely to relate to the time required for the initial settling of the plots after the construction of the mock-up archaeological sites, which seems to have resulted in a rapid occurrence of damage at the beginning of the trial, before the plots settled down to a more typical, slower rate of truncation.

Comparison between techniques with regard to damage, protecting sites and soil structure

Primary tillage

In terms of damage to the plots, mouldboard ploughing to 0.20-0.25 m was obviously the most destructive form of primary cultivation, followed by shallow ploughing. By Year 3RT, when the real time plots were excavated the mouldboard plough had reached *c* 0.30 m below the ground surface. By year 24 in the accelerated plots it had reached 0.40 m, as evidenced by the disturbance to the secondary fills of the archaeological features and seen on the surface. Excavation confirmed disturbances at this depth. This clearly indicates that unless there is a very large buffer of soil between the plough surface and archaeological layers, ploughing to a ‘normal’ depth is not a sustainable way to protect archaeological sites.

Shallow ploughing to a depth of 0.125 m within a reinstated ploughsoil of 0.25-0.30 m did not cause damage to the underlying archaeological deposits during the 3 years of cultivation in the real time plots. However, in the accelerated plots warnings of damage was consistently occurring after 5 years, indicating disturbance to a depth of 0.20-0.25 m, with one station showing a warning by Year 2A. By Year 6A, and consistently thereafter, actual damage was occurring, proving that ploughing had reached 0.25-0.35 m below the pre-cultivation ground surface. By Year 30A it had extended to 0.37 m (ploughsoil depth plus truncation) truncating the archaeological features by an average of 0.07 m. Even in the real time trials a gradual increase in the disturbance of the warning layer placed at 0.20-0.25 m was seen, from 1 case of disturbance in Year 1 to 3 in Year 3. Once again, unless there is a large buffer involved, shallow ploughing over time, particularly in the wetter years, will also cause damage to underlying archaeological deposits and is not the answer to long term preservation of sites.

Truncation appears to be mostly gradual over time, with significant enhanced damage caused by specific truncation events such as might be occasioned by working wet soil. Whilst an increase in damage may be expected during wetter years, a variety of other reasons have also been put forward to explain the more gradual truncation. Restriction of plough depth is often seen as an effective way to protect archaeological sites, but these results show that this is not sustainable over time. It is also notoriously difficult for even experienced ploughing practitioners to maintain a set or shallow depth when ploughing, which usually means that restricted depths are exceeded and/or are only erratically adhered to. It has also been suggested that gradual damage could be caused year by year through the soil movement created by the forward movement of the plough each time the plot was ploughed. It is likely that the truncation of the archaeological sites to an average depth of 0.10 m over 30 years was caused by a combination of these factors, all of which would be applicable in real arable fields.

Neither non-inversion tillage nor direct drilling caused truncation to archaeological deposits over the lifetime of the project and on the basis of these results are unlikely to cause such damage over a considerable timeframe. However, the issue of the necessity for subsoiling is obviously key here. This is discussed further below.

Subsoiler damage

The evidence from all the plots shows that subsoiling is tremendously damaging to archaeological features and artefacts. The more the plots were subsoiled then the more damage occurred. Where the subsoiler has wings, as had the one used in the trials, at the level of the wings it can cause damage to the features by dragging and mixing of the deposits, making interpretation of features over time difficult or impossible. This can be seen in the distortion of the shapes of the postholes and removal of slices of the ditch fills, and in some cases the removal of some of the postholes from view altogether. The strength of the subsoiler also caused scarring of the stones of the wall and the breaking up of these stones, so that they appeared as small chunks on the surface of the soil. The subsoiler also displaced the wall stones considerable distances, both vertically and horizontally. Movement and destruction of artefacts was also seen in the removal of some of the pots from the plots altogether, and their destruction when they lay in the path of the subsoiler.

Below and above its wings the subsoiler causes less soil movement. Here the subsoiler tine is V-shaped to ease its way through the soil; once it has cut through the soil it slumps more or less back into place. This causes less soil movement, in that the tine itself does not drag soil over distance, but it is no less destructive to more robust elements like the wall and artefacts.

Subsoiling - background

Farmers have used methods for disturbing the sub-soil to depths of 0.30-0.50 m since the availability of mechanical powered cultivation, the main purpose of which has been to restructure either naturally occurring dense sub-soil or specific pans (where the soil both above and below the pan is at a lower bulk density). These operations are intended to permit the passage of roots, oxygen and water to deeper layers in the soil and hence remove any mechanical impedance that may restrict crop growth and development. During the 1950s and 1960s agricultural mechanisation developed significantly with relatively little concern for the effect on soil structure. This continued until the wet harvest period of 1968, when soils were seriously damaged. As a result the Strutt Report was commissioned that recommended further action should be taken to remedy the problems. One result was a number of detailed studies into the physical and agronomic benefits of shallower soil loosening rather than deep subsoiling.

Simultaneously other studies (Soane *et al*. 1981a; 1981b; 1982) were established to understand and reduce the extent of soil compaction caused by the increasing weight of farm machinery. Since then farmers have been encouraged to “tread as lightly as possible” on the soil and to use deep soil loosening (subsoiling) operations sparingly. This has not always been possible, and a period of “recreational deep tillage” took place during the late 1970s and early 1980s, with the availability of increased tractor power. During this time significant damage will have been inflicted on archaeological deposits to depths of 0.40 m.

For reasons of time and cost considerations recent developments have seen an increase in both minimum (shallower, non-inversion) tillage and direct drilling, with a corresponding reduction in the use of mouldboard ploughing. Many farmers are also aware of soil compaction issues and will purchase tractors with large section tyres (with potentially lower inflation pressure) or rubber tracks to avoid compaction issues. Whilst these are a significant advantage (Ansorge and Godwin 2007) they cannot always provide a solution in the wettest/weakest soil conditions. Currently the early adoption of both: 1. central tyre inflation systems, to enable reduced pressures at low speeds in the field and increased pressure for road speeds and 2. controlled traffic systems, to concentrate wheel passes; help alleviate some of the longer term problems. Therefore, in appropriate areas there is now a move towards less intensive and more conservation orientated approaches to production with grants offered through agri-environment schemes to facilitate this process.

Panning and the need for subsoiling

The data collected here from the re-excavation of the archaeological sites, penetrometer readings and bulk density samples show no evidence of the formation of pans, ie horizons where the soil strength/density increases significantly with depth and then decreases again. In nearly all cases the soil strength continues to increase with depth to expected levels for this soil type and moisture content range (Soane *et al*. 1986; Lampurlanés and Cantero-Martinez 2003).

In fact the penetrometer data from this study indicate that it is the mouldboard and shallow ploughing operations that are likely to reduce the natural soil strength and make soils more vulnerable to compaction. The shallower non-inversion tillage and direct drilling carried out here were found to result in retention of a higher level of natural soil strength and make it less prone to compaction. In terms of archaeological protection this could mean that on sites where minimum or no-till practices were adopted, the soils were at lower risk from compaction and less likely to require remediation measures (eg subsoiling). Where localised pans were created below wheelings in the ruts (the only place where compaction seen, and extending a maximum depth of *c* 0.20 m, although the average was much less) these could easily be removed by selective shallow subsoiling or loosening just to the depth of this compaction. It is better, however, to prevent the formation of ruts and pans in the first place by following the recommendations laid out in Section 7 (see also Appendix 5) and in Defra's Guide to good soil management (Defra 2009).

Validity of Results

Evidence for truncation of archaeological features by cultivation was assessed by comparing pre- and post excavation sections and by comparing levels OD taken prior to and after cultivation. Whilst every effort was made to both accurately record and excavate these details, given the nature of soils and excavations, especially the process of cleaning, errors in the form of slight over-excavation or slight errors in the surveying may have occurred. Given this possibility, all measurements of depths of truncation etc have been averaged out for each plot using both survey and section information. An error of plus/minus 0.02 m should also be added to all results discussed below to take into account the potential errors mentioned above.

Given the basic correlation between the real time and accelerated plots discussed above, the applicability/relevance of the accelerated plots is that they are likely to reflect, at least in broad terms, what would happen to an archaeological site just below the ploughsoil on this type of soil over a period of 30 years.

The accelerated nature of the trials may have caused some loss of soil structure in the later years, which therefore has an effect on some of the results, though most weakening is likely to have been a consequence of high moisture content levels. In any case this affects neither the validity of the accelerated trial process nor the overall conclusions of this work. The archaeological damage recorded is suggested to have resulted from a combination of gradual attrition accelerated by deeper truncation caused by bad soil management events (eg cultivation during wet weather), circumstances which are quite typical of the nature of truncation of archaeological sites resulting from long term mouldboard ploughing.

Further data on these issues are provided by the comparative analysis of the bulk density and penetrometer results from the real time and accelerated trials. Whilst they show some differences, these do not suggest that the condition of the soil in the accelerated trials was significantly worse than in the real time trials; the soils were still workable. The penetrometer readings from the accelerated trials, whilst higher than those from the real time sites, showed no build up of pans over the notional 30 year cultivation period in any of the accelerated plots (away from the wheelings).

It would therefore be fair to postulate that the results of these trials are representative of the "lighter" third (higher sand/lower clay content) of the soils of England. They may also represent other "heavier" (higher clay contents) soils that have the annual opportunity to re-structure through the normal wetting and drying cycles, as long as good soil management is practised so that these clay soils are not worked in extreme conditions.

The rates of truncation discussed here are comparable with those seen where they have been recorded from real sites, further enhancing confidence in the reliability of these results. For example, 40 years worth of truncation at Gosbecks averaged out at 0.004 m of truncation a year, 80 years worth of truncation at Barrington averaged 0.002 m a year and at Whitley Grange truncation over 100 years averaged *c* 0.004 m a year. The results of the accelerated trials, with its long term average of 0.003 m of truncation a year, therefore appear to correlate well with real data recorded elsewhere. Interestingly, truncation recorded over 5 years at Bishop's Canning reflected much more closely the average truncation recorded in the 3 year real time trial site. At Bishop's Canning the average truncation recorded was 0.02 m a year and in the 3 year trial the average is 0.01 m. These high figures (compared to the average derived from the accelerated trials and comparable sites just discussed) suggest that truncation is at its most rapid in the early stages of taking land into cultivation. Over time, truncation may settle down to a slower average rate, encompassing periods of accelerated truncation as well as periods of minimal and perhaps no truncation. There is no suggestion, however, that the ploughsoils will become stable to the point that there is no ongoing truncation over sustained periods of time.

Conclusions

Rates of archaeological truncation over time were recorded at:

- Accelerated mouldboard plough plots 0.10 m over 30 years - 0.003 m a year.
- Accelerated shallow plough plots 0.07 m over 30 years - 0.002 m a year.
- Real time mouldboard plots 0.03 m over 3 years - 0.01 m a year (this faster rate may indicate an initial period of settling).

These rates are similar to those seen on real archaeological sites where truncation has been recorded.

Some other conclusions are that:

- Both deep and shallow mouldboard ploughing operations will damage archaeological sites damage over time - as demonstrated in both the accelerated and real time trials. This is likely to be caused by a combination of long term truncation through the difficulties in maintaining an exact plough depth (especially if working at a restricted depth), soil movement created by the forward movement of the plough and more dramatic truncation during cultivation when moisture levels are high (above 20%).
- The mouldboard ploughed plots showed significantly greater soil depth disturbance when primary cultivation occurred at times of higher moisture contents. This is probably caused through 1) a combination of some sinkage of the tractor wheels (although this was minimised by using large section tyres at relatively low inflation pressures) and 2) the decreased capacity of the soil to maintain the weight of the plough, causing it to operate at greater depths.
- The study shows no development of compaction pans away from the wheelings in any of the plots including the direct drill and non-inversion tillage even after 30 years of primary and secondary tillage, although relatively compact subsoils did result.
- Conventional and shallow ploughing operations are likely to reduce the natural soil strength and make soils more vulnerable to compaction. The shallow non-inversion tillage and direct drilling carried out here were found to result in retention of a higher level of natural soil strength, making it less prone to compaction.
- More carbon is retained in the plots where cultivation works the soil the least.
- All types of cultivation affect the density of the soils over a 30 year period, but direct drilling and shallow ploughing tend to have the least overall effect.
- Direct drilling and shallow non-inversion tillage will offer long term protection over archaeological sites if they are sustainable without the need for subsoiling below the implement depth.
- There is evidence to suggest that shallow subsoiling/deep tillage/loosening to a depth of 0.25-0.30 m will remove the effects of shallow soil damage caused by surface wheelings. It is probably only the single grain structured sandy loams and similar soils that will need this aftercare as many clay soils in England will naturally crack and restructure during subsequent drying periods. It is better, however, to prevent the formation of compaction damage in the first place by following the recommendations in Appendix 5 and the Defra code of good soil management (Defra 2009)
- Subsoiling will cause significant damage: 1) to buried artefacts when the implement tines come into direct contact with the objects and 2) from the dragging and mixing of deposits.
- Moisture is a key factor affecting damage. High moisture levels in the soil can lead to higher pressure transference, rutting and compaction in the wheeelings. The consequent reduced soil strength can lead to the plough penetrating deeper into the ploughsoil.
- Much damage can be avoided through following Defra’s good soil management code (Defra 2009).

5 Earthwork Studies

Introduction

The 'humps and bumps' seen within agricultural fields can reflect a wide range of archaeological sites; prehistoric barrows, the ramparts of Iron Age hillforts, Roman forts, medieval castle mounds, moats, lanes and evidence of previous agriculture in the form of ridge and furrow, field boundaries and lynchets etc. The loss of earthworks, historical farm buildings and field boundaries - the visible components of heritage - from the landscape, constitutes a lessening of individual regional character and reflects the spread of a more homogeneous modern agricultural landscape. Earthworks are also important in offering protection to potentially well-preserved archaeological features and palaeoenvironmental remains beneath them. With the development of mechanised ploughing over the last 50 years, there has been a significant reduction in the survival of earthworks within our rural landscape (English Heritage 2003). Many of the earthworks that were identified and scheduled during the post-war era are now found to be ploughed and are either only identifiable as cropmarks or survive as small upstanding undulations in the landscape.

Modern farming techniques inevitably degrade earthworks by:

- The preparation (including bulldozing) of earthworks prior to cultivation

- Cultivation which can flatten earthworks and disturb buried deposits and features within them
- Lateral encroachments at the edges of earthworks which can help erode them and which will eventually lead to their destruction. This can lead to misunderstanding of the interpretation of the earthwork
- Soil erosion on earthworks and slopes which reduces ploughsoil depth on the upper and mid slopes and enhances the risk of damage to archaeological deposits below by further cultivation. Defining the degree of slope likely to be susceptible to soil erosion is important when trying to predict archaeological survival. Anything in the mid-slope range upwards (eg 5 degrees and upwards) is likely to trigger soil movement, therefore making archaeological sites on these slopes vulnerable to damage. The occurrence of erosion on less steep slopes is less easily predicted and depends much more on a complex combination of variables which may include the type of soil, drainage, cultivation regime, compaction, crop cover, location and nature of field boundaries, time of sowing etc.

Once earthworks are degraded then the ‘threshold effect’ comes into play. This is relevant to earthworks, but also to all archaeological sites under the plough and describes a situation in which a single season of plough-induced truncation can wipe out the remaining, and perhaps the most important, evidence of an archaeological site. With earthworks it can be particularly hard to judge when this stage is reached. With small, often scheduled, upstanding mounds it is often difficult to tell if the earthworks represent only raised areas of natural subsoil which have in the past been protected by a mound that no longer exists, or whether they contain archaeological evidence which it would be worthwhile to continue to preserve. If archaeological remains do survive, these rather unimpressive monuments are very vulnerable to destruction. Only one episode of slightly deeper-than-usual cultivation could destroy any surviving mound material or buried soil, and therefore destroy any archaeological evidence that there was once a feature at this point. There are relatively few data relating to annual rates of truncation from ploughing and other agricultural activities, but this information has been recorded for some monuments. These records suggest typical rates of truncation of 0.02-0.05 m per year (OA 2002).

Aims

The main aims of the earthwork studies were to:

- Assess the effects of different tillage operations on the survival of a range of earthwork forms
- Test whether the adoption of non-inversion tillage or non tillage cultivation could be used as an alternative to conventional ploughing or pasture in order to offer greater protection to archaeological earthworks
- Make recommendations that would help to protect earthworks that are currently within arable fields (Section 7)

Methodology

A range of earthworks were constructed for this study. A detailed account of this can be found in Appendix 4. The earthworks did not replicate the original form of the monuments simulated, but rather their condition as it would have been after they had already been in cultivation for a while, but were still visible and archaeologically viable. Monitoring stations of a character appropriate to the associated cultivation type were installed in the same ways as for the flat sites.

Earthwork	Original Dimensions as constructed	Cultivation	Modifications for cultivation
Ridge and furrow	32 m wide at frequency of 10-20 m and amplitude of 0.45 m	Non-inversion (+ 4 m fallow)	32 m wide at frequency of 10-20 m and amplitude of 0.40 m
Round barrow	16 m diameter and 1 m high	Direct drill (0.05 m)	20 m diameter and 0.80 m high
Round barrow	16 m diameter and 1 m high	Non-inversion (Simba Solo 0.10-0.15 m)	20 m diameter and 1 m high
Round barrow	16 m diameter and 1 m high	Ploughed (0.20-0.25 m)	20 m diameter and 0.60 m high
Round barrow	16 m diameter and 1 m high	Fallow	16 m diameter and 1 m high
Ridge/bank	34 m long, 10 m wide, 0.55 m high	Non-inversion and ploughed (+ 4 m fallow)	34 m long, 10 m wide, 0.50 m high
Slope	2.5-3.2 degrees	Non-inversion and ploughed	

Table 1: Dimensions of earthworks and cultivation type

Cultivation and management

A total of 6 sets of 5 cultivations were carried out over each earthwork over a 2 year period at varying intervals of time but allowing time for the soil to settle between each set. Thirty years worth of non inversion tillage cultivations were undertaken on all the earthworks – barrow, ridge, slope and ridge and furrow, with the exception of the direct drill barrow which was cultivated for the equivalent of 20 years only. Both the ridge and furrow and the ridge were cultivated across the earthworks, ie perpendicular to their alignment. Weed growth was allowed on the earthworks throughout the year till they were sprayed off using Glyphosate (Round up) prior to the autumn cultivations in July 2006 and again in early August 2007.

Recording and monitoring

Every pass of the tractor during the cultivation phases was monitored to check whether any of the glass chips or sand was being brought to the surface. These materials were of 3 colours, representing disturbance to three depths, depending on the cultivation type, and indicating that disturbance had reached a certain depth. After the equivalent of every 5 years of cultivation any movement of the transponders was plotted so that soil movement could be analysed. A detailed contour survey was undertaken at the pre-cultivation stage, after year 1, and at every 5 year interval up to 30 years. After the final GPS recording of the altered earthwork profiles, sections across the area of the earthworks and monitoring stations were excavated by machine (JCB with ditching bucket) and the results recorded.

Results

Cultivation smoothed out the original profiles and gradually reduced earthwork gradients and heights. Tillage was observed first to attack the upper slopes and edges of the earthworks. Monitoring of the glass and sand allowed an analysis of the depths of disturbance over time. Soil displacement was generally recorded on the top and upper slopes of the earthworks, with the lower areas less affected at first. Some of the lower slopes were then protected by soil displaced from the upper slopes. The gradual truncation of the earthworks is shown in Table 2, while Table 3 summarises the overall extent of truncation and changes to each earthwork.

Earthwork	**pre-cult height**	**height after year 1**	**height after year 5**	**height after year 10**	**height after year 15**	**height after year 20**	**height after year 25**	**height after year 30**	***Total Loss***
Barrow (no cult.)	1.0 m	1.0 m	1.0 m	1.0 m	1.0 m	1.0 m	0.97 m	0.95 m	*0.05 m*
Barrow (non inv.)	1.0 m	0.94 m	0.9 m	0.80 m	0.70 m	0.50 m	-	0.39 m	*0.61 m*
Barrow (direct drill)	0.80 m	0.80 m	0.80 m	0.78 m	0.76 m	0.75 m	NR	NR	*0.05 m*
Barrow (plough)	0.60 m	0.65 m	0.66 m	0.50 m	-	0.46 m	0.36 m	0.20 m	*0.40 m*
Ridge and furrow (non inv.)	0.40 m	0.35 m	0.25 m	0.05 m	-	-	-	-	*0.35 m*
Ridge (non inv.)	0.50 m	0.45 m	0.41 m	0.36 m	0.32 m	0.26 m	0.19 m	0.14 m	*0.36 m*
Ridge (plough)	0.50 m	0.43 m	0.37 m	0.27 m	0.25 m	0.21 m	0.15 m	0.08 m	*0.42 m*

Table 2: Height changes in earthworks over time

Type of earthwork	**Left standing**	**Total height loss**	**Average height loss per 5 years**	**Average annual loss**
Barrow (no cult)	0.95 m	0.05 m		
Barrow (non inv.)	0.39 m	0.61 m	0.10 m	0.02 m
Barrow (direct drill)	0.75 m	0.05 m	0.008 m	0.002 m
Barrow (plough)	0.20 m	0.40 m	0.06 m	0.01 m
Ridge and furrow (non inv.)	0.05 m	0.35 m		0.03 (over 10 years)
Ridge (min inv.)	0.14 m	0.36 m	0.06 m	0.01 m
Ridge (plough)	0.08 m	0.42 m	0.07 m	0.01 m

Table 3: Overall summary of truncation

Comparison between earthwork types

All earthworks showed relatively more truncation in Year 1 than in all other individual years. This was presumably in part a result of the settling of the earthworks under the weight of the machinery used in the first cultivation pass. Whilst the general results are similar (ie both ploughing and non-inversion tillage on an earthwork will gradually erode it, with the ploughing doing so slightly more quickly), each earthwork was found to respond slightly differently to tillage as the shape, wavelength, and break of slope were all significant factors in their response. For example, the non-inversion tillage ridge and furrow very clearly went through a two stage process of truncation. Prior to Year 10 truncation happened at a rate of 0.025 m a year. Once the earthwork was reduced to a height of 0.25 m, it was virtually destroyed in 5 years, a truncation rate of 0.04 m loss per year. The rapid rate of truncation reflected the fact that once the earthwork height reached 0.25 m it fell within the range in which the Simba Solo was at its most effective in removing such an obstacle. A further factor was that the wavelength of the earthwork did not allow enough time/distance for the tractor and implement to ride over the soil. This meant that the upper slopes of the ridges were, in effect, subject to a more intense planing/levelling off due to the equipment's lack of vertical articulation; the cultivation implement simply followed a relatively flat line through the earthwork.

A similar acceleration of truncation was also seen in the barrow which was subject to non-inversion tillage. Here the rate of truncation was 0.04-0.06 m over the first 6 years (with barrow height 0.9-1.0 m) which rose to 0.1 m in Years 10-15 (barrow height 0.7-0.8 m) and to 0.2 m in Years 15-20 (barrow height 0.5 m). No truncation was seen in the period of Years 20-25, but truncation occurred again between Years 25 and 30, with a loss of 0.11 m resulting in a final height of 0.39 m. Given the original height of the barrow, cultivation did not occur over a long enough period for it to be possible to see what would have happened once the apparently critical height of 0.25 m was reached (at which point very rapid truncation followed in the ridge and furrow) or indeed whether the isolated barrow feature would have responded in the same way as the ridge and furrow.

A similar phase of rapid destruction did not occur on the non-inversion tilled part of the ridge. Here the rate of truncation was more gradual and consistent throughout the 30 year accelerated trials period, being consistently *c* 0.04-0.07 m in every 5 year period. It appears, therefore, to be the wavelength of the ridge and furrow which has affected its rate of its destruction. In the case of the ploughed barrow and ridge no patterns were discernible in the chronological trends of truncation, although both showed a slightly increased level of truncation at Year 10.

The shapes of the barrows were rapidly changed. For example the non-inversion tillage barrow changed from a circular feature to a comet-shaped feature extending in the direction of tillage. Such changes may lead to erroneous interpretations regarding the location of the centre point and the original position of an earthwork. The plough barrow not only showed an increase in length but also developed very distinctive steps, seen especially clearly in Years 10, 25 and 30. Similar steps were seen briefly in the non-inversion tilled barrow, most clearly in Years 5 and 10, before they were planed away. These features reflect where the weight of the tractor caused a collapse of the vulnerable edges of the earthwork.

Summary of comparison between cultivation types

The tables above show that the average rate of truncation per year for the ploughed earthworks was 0.01 m. Truncation of the earthworks subject to non-inversion tillage varied, depending on the type of feature cultivated, but ranged from 0.01-0.03 m per year, with the ridge and furrow most severely affected at 0.03 m a year. For the two directly comparable earthworks, the barrow and the ridge, the data for the ridge show the same average overall rates of truncation for both types of cultivation, while for the barrow the rate of truncation was higher using non-inversion tillage.

One of the reasons for the examination of the non-inversion tillage technique was to see if it would be an effective way of minimising damage to earthworks if they remained in cultivation. These studies have proved that non-inversion tillage does not offer a sustainable solution to keeping earthworks in cultivation, and in some cases can actually cause faster levels of truncation than the mouldboard plough. Direct drilling is the only sustainable method by which earthworks can be kept under cultivation. This reflects the fact that the Simba Solo is designed to flatten irregularities and the flattening of earthworks seen here is typical. This was exacerbated in the present case by the geometry of the cultivator-tractor combination in relation to the size of the earthworks. The trailed design of this cultivator forces the discs to penetrate more deeply into the earthworks as the relative motion of the tractor drawbar pitches downwards when the tractor leaves the earthworks, pulling more soil forward than in the steady state condition. A similar effect could also occur upon entry to the earthwork as again the drawbar hitch point pitches downwards.

Survival of features below earthworks

The glass and sand indicator stations showed the depths of disturbance reached by each form of cultivation and clearly showed where most of the disturbance and soil movement occurred. In the early stages of cultivation discernible disturbance was concentrated on the top and upper slopes of the earthworks. The lower slopes were affected later, but in some cases these then became protected from further disturbance by the re-deposition of the soil from the upper parts of the earthworks.

Once these experimental earthworks were destroyed to the point where cultivation penetrated the depth of the remaining earthwork material then the buried soil was vulnerable to destruction. The buried soil is likely to be better protected under non-inversion tillage once the site is flat and if the depth of soil cover is greater than the depth of the tines. Any buried soil under ploughed earthworks stands less chance of survival once the earthwork exists as no more than the depth of ploughsoil; the rates of truncation seen on the flat sites will apply. Earlier partial destruction could also occur at the edges of the earthworks as cultivation equipment digs into their sides. This was seen in the plough barrow when it was 0.5 m and 0.36 m high. However, whilst this work shows what may happen to buried soils and features under an earthwork over a 30 year period this cannot totally recreate the circumstances of hundreds of years of cultivation and other impacts on earthworks, such as solution, long term tillage erosion, animal disturbance and bioturbation.

Validity of Results

No significant slope truncation or soil creep was recorded during the trials. It is likely that the slope was either not really steep enough for erosion to happen within this soil type, and/or that cultivation was not prolonged enough to show significant changes of this kind. However, colluvium was seen on the site, so there has been some soil erosion in the past, but no significant erosion incidents occurred in the life of the project and it is quite possible that any changes of this nature would have occurred at a rate too gradual to be recorded within the timescale of the project. Nevertheless, assumptions based on the understanding of soil erosion and the results of the trails carried out here have allowed recommendations for arable agriculture on slopes to be made. It is thought that these are realistic, based on the variables stated. The recommendations and assumptions have been included in the recommendations section, section 7.

Whilst the authors cannot be categorical about extrapolating these findings to earthworks built from other soil types it is reasonable to assume that, because of the physical effects of the tillage tools used, soil movement would be independent of soil type and the results apply equally to other soils. One major factor would be the effects of *in situ* soil strength, which could restrict the operational depth of tillage with higher clay content and drier soils.

In the rare cases where the rates of truncation of earthworks under cultivation in the ‘real world’ have been recorded they appear to be similar to those recorded here. The average annual truncation rates vary from 0.01 m at Thornborough Henge, to 0.02 m for barrows in Norfolk and 0.04 m for a Neolithic causewayed camp in West Sussex. Whilst the circumstances and type of cultivation are not necessarily stated, the assumption is that these sites have been ploughed rather than subject to other types of cultivation. Given the possible variables the rates seen in these examples and in the present study are comparable.

Conclusions

Based on the results of this study the following inferences can be drawn:

- Ploughing does not allow the preservation of earthworks
- Non inversion tillage of earthworks does not offer significant protection to earthworks compared to conventional ploughing
- Zero/No-tillage (direct drilling) was found to offer the only long-term sustainable protection for most earthworks if they remain in cultivation
- Managed pasture forms the only other sustainable protection for earthworks, although increased bioturbation may be an issue
- The average height loss of the non-inversion tilled earthworks is *c* 0.01-0.03 m per year, the variation correlating significantly with earthwork type
- The average height loss of the ploughed earthworks is *c* 0.01 m per year
- Truncation of the earthwork, especially leading to the redistribution of the soil over a wider area in the direction of cultivation, may lead to miscalculation of the location of the original centre point (and thus, for example, of the position of a burial beneath a round barrow), and over a long period may lead to misconceptions as to the original position of the mound
- Buried soils and features below earthworks are likely to be affected at the edges of the earthwork first
- Once earthworks have been ploughed/cultivated flat then any features beneath them will survive better under non-inversion tillage than ploughing, as seen in Section 4.
- Even severely plough-damaged earthworks can preserve buried soils, artefacts, burial features beneath them

Earthworks located on a slope or on a lighter sandy or sandy loam soil may be prone to greater rates of truncation because of their natural erodibility. This could have a differential effect depending upon the geometry of the earthwork, with steeper slopes on the downhill face and shallower slopes on the uphill. Some earthworks, which tend to follow the contours, such as ridge and furrow, could act as soil conservation terraces and help to reduce gradual downslope drift.

6 Monitoring

Aims

A series of monitoring stations containing differing materials as discussed in Section 4 were installed in order to monitor depths of disturbance. A variety of different sizes of monitoring stations and configurations using glass, sand and radio transponders were used to test which system will be most effective for use in the field by advisors monitoring cultivation depth.

Results

The sand and glass indicator stations performed equally well in having their contents brought to the surface when disturbed by the plough. Those in the non-inversion plots were less responsive, although some material was brought to the surface by the Simba Solo. Once on the soil surface the glass remains a fairly prominent feature whereas the sand tends to disappear quite quickly (mixing and infiltrating into the soil matrix), and will do so very quickly if it rains. Glass is therefore better at providing a lasting indication of warning or actual damage.

The glass and sand from the 1 m square indicator pits appeared slightly more regularly at the surface than the materials from the 0.5 m equivalents. For example, the 1 m sand pit showed visible fresh disturbance indicating actual damage 16 times and the 0.5 m pit 13 times. The visibility and effectiveness of the glass in the shovel pits was variable in that one of the pits was visible 14 times in total and the other only 7. The 1 m glass indicator station was the most effective form of monitoring station in that material from it was brought to the surface most often (or recognised most consistently - 29 years) and lasted the longest (30 years). The results suggest therefore that if the right indicator station size and fill type is selected, and assuming a 0.05 m depth of glass in each layer, monitoring can continue up to 30 years. Other sizes and materials will be effective from *c* 15-25 years.

Disturbance of the transponder stations was seen throughout both the mouldboard ploughed and non-inversion tillage plots. Transponders are as responsive as glass and sand in the ploughed plots, and more so in the non-inversion plots, are cheaper to install and are more tamper proof. However, the equipment needed to track them is relatively expensive, they are prone to damage and locating transponders once they have moved can be time-consuming.

Conclusions

The relative costs of each monitoring method are shown (ordered by cost) in Table 4.

Method	**Price (2009 prices)**	**Time taken**	**Assumptions**	**Total**
1 m glass - glass	Glass £30 Beacon Transponder £5.20	1hr	25kg glass per layer = £15, 2x layers = £30	£35.20 plus 1 hour
0.5 m glass	Glass £16 Beacon Transponder £5.20	0.5hr	6.5kg glass per layer = £8, 2x layers = £16	£21.20 plus 0.5 hour
1 m sand	Beacon Transponder £5.20 £8 sand	1hr	25kg sand per layer = £4, 2x layers = £8	£13.20 plus 1 hour
Transponder station - compass	Beacon Transponder £6.95 4x 32mm = £5.52	0.25hr	32 mm glass transponders = £1.38 each	£12.47 plus 0.25 hour
Transponder station - point	Beacon Transponder £6.95 3x 32mm = £4.14	0.25hr	32 mm glass transponders = £1.38 each	£11.09 plus 0.25 hour
Shovel pit	Glass £1.00	0.25hr	1kg glass pr layer = £4 2x layers =*c* £8	£8.00 (or 13.20 with a beacon transponder) plus 0.25 hour
0.5 m sand	Beacon Transponder £5.20 £2 sand	0.5hr	6.5kg sand per layer = £1, 2x layers = £2	£7.20 plus 0.5 hour

Table 4: Relative costs of each method

Neither method relies on transporting bulky equipment to a field and all types of monitoring station can be located using a handheld global positioning system for a rough location then using a transponder reader to locate the locator beacons within the glass/sand pits and the transponder configurations.

In terms of methodology, monitoring the sand stations would have to be carried out directly after primary cultivation, as the sand will not remain visible for long on the soil surface. The timetable for glass would have more flexibility, although operations subsequent to primary cultivation would tend to disperse the glass and make any concentrations less distinct. Evidence for both the sand and glass on the surface of the plough soil could also be removed by a farmer. The transponders (32 mm glass cylinders in point configurations) could be used as a way of cross-checking compliance. Monitoring of the transponders could be done at any time after primary cultivation without fear that the evidence would disappear or be tampered with.

It may be that the two techniques would be best used in combination. Glass would be used to show the farmer that he was getting close to the archaeological deposits so that he could “self-regulate”. The transponders could then be used as a way of cross-checking compliance if buried just below the stated cultivation depth, but a number of stations would need to be inserted to ensure reliability.

Recommendations and Conclusion

Where farmers and land managers are aware of the presence of buried archaeological features, deposits and artefacts in cultivated fields, they should:

Avoid mouldboard ploughing - i.e tillage operations which invert the soil

Use shallow tillage and direct drilling (no/zero tillage) operations with tractors equipped with wide section tyres, low ground pressure or dual tyres or rubber tracks

Where possible use harvesters, tractors and trailers equipped with rubber belted tracks or the largest possible tyre diameters and section widths and or dual tyres or tandem/ triple axles to reduce the load per tyre

a. Operate all field going equipment with the safest low inflation pressure for the required load and field/road speed duty cycle

b. Consider using central tyre inflation pressure systems where there are conflicts between field and road going speeds, as can be the case with pea harvesters and tractors and trailers undertaking both field and road transport of produce

Where practicable concentrate as many wheelings as possible in one place and apply the principles of controlled traffic farming

Prevent road going trucks with tyres with high inflation pressures from traversing the fields; permit them to park on the headland by the gateway

Discharge crop harvesters to trucks and trailers located on the headlands or alternatively reduce the load in harvesting trailers and “chaser wagons”

Where possible avoid field operations in high moisture content conditions with weak soils at or above field capacity

Only undertake subsoiling operations to depths no greater than 0.30 m (12”) or within the current depth of ploughsoil - whichever is least as they can damage buried archaeology by direct impact

Non-inversion tillage of earthworks using a combination tillage tool (discs and tines, eg the Simba Solo) does not offer significant protection to earthworks compared to conventional mouldboard ploughing. When farmers and land managers are attempting to preserve earthworks, direct drilling (no/zero tillage) and managed pasture are the only feasible options

On slopes neither conventional nor shallow ploughing should be undertaken, for the same reasons as for flat sites

Whilst non-inversion tillage is damaging to earthworks due to its capacity to move and level irregularities, it can be used on slopes with the following caveats:

- Non-inversion tillage, or indeed any tillage, should not be undertaken on the upper and middle slopes where the slope is more than 5 to 6 degrees (direct drilling may be possible but should be assessed on a case by case basis). This is especially relevant on predominately fine sand and silty soils where the risk of soil erosion is greatest. Soils with higher clay content may be cultivated, but they would also need to be assessed on a case by case basis depending on the history of erosion and soil depth
- Non-inversion tillage must be undertaken either along the contours of the slope or approximately perpendicular to the main field slope, and not up/down slope
- Good slope tillage management should be adhered to: ie tillage should be practised in one direction one year and the other direction the year after. This will compensate for any small movements of the soil

All of the above recommendations support the principles of good soil management, which help to sustain good agricultural practices by minimizing compaction and promoting crop growth whilst attempting to preserve the buried archaeological resource.

The above recommendations apply to all soil types, albeit that the quoted “erosion losses” may be higher on the sandy soil used in this study than on soils with higher clay contents. Similarly the deeper subsoil pressures in the clay field were marginally less than those in the sandy loam soil in the laboratory.

Follow the Defra guidelines in *Protecting our Water, Soil and Air: A code of good practice for farmers, growers and land managers* (Defra 2009).

It can be seen from the recommendations set out above that the objectives outlined in the introductory section have been met. This work suggests practical measures which will now underpin policies of heritage protection, arising from developments in the Planning Policy Guidance and heritage legislation.

Future Work

One of the key issues facing those involved in making management decisions is how to prioritise which sites to protect, especially earthworks. How low does an earthwork have to be before buried soils and shallow features beneath them have been destroyed by cultivation. This work has considerably enhanced our knowledge of what happens to an earthwork during cultivation and has provided some indication of the extent of survival beneath a cultivation truncated earthwork. However, the work of trials, while giving a good impression of the effects of cultivation over a 30-year period, cannot totally recreate the effects of hundreds of years of cultivation and other ongoing erosion issues on earthworks and the consequent survival of buried soils. Further work could therefore be carried out on a limited number of denuded earthworks, which lie at the threshold of where we think buried soils and features may, or may not, survive, to examine the extent of survival under these earthworks. This would involve putting a suitably sized trench across a number of earthworks, reflecting different earthwork types, cultivation systems and topography and geology.

The responsiveness to transponders to disturbance by the subsoiler was not tested. One of the key issues is how to monitor whether subsoiling is taking place, and the use of transponders in this process could be tested in a further small-scale trial.

Knowledge Transfer

As part of this project OA and Cranfield will be producing articles for *European Archaeology*, a Soils journal and a Farming journal and 3 papers for either the *Journal of Terramechanics*, *Biosystems Engineering*, *Soil and Tillage Research*, or *Soil Use and Management*. A package of initiatives is currently being worked up with English Heritage to further publicise the results of this work, especially to the farming community.

The results of this work will also be critical for those involved in providing management advice for archaeological sites in arable landscapes, including Natural England and English Heritage. This report provides them with tried and tested recommendations based on actual results, rather than hearsay, which can be discussed with farmers and other land managers and implemented through agri-environment schemes.

The management recommendations discussed here will feed into recent work by OA developing risk assessment procedures for archaeological sites in arable (COSMIC). Where sites are identified as being at high or serious risk attempts will be made to try and get farmers to adopt the informed recommendations developed here.

The work that has been carried out here examining pressures at depths will also be relevant to those in cultural heritage management generally. The principle behind all development control work is that where possible significant archaeological sites should be left intact and preserved *in situ*. However, there have been increasing concerns raised about whether this is a sustainable option in circumstances where buried ‘preserved’ sites are put under considerable pressures by development. The present work will inform this debate and Cranfield and OA have already contributed to these discussions in a seminar organised by English Heritage on the potential effects of compression.

References to published material

9. This section should be used to record links (hypertext links where possible) or references to other published material generated by, or relating to this project.

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