A soil quality comparison from agriculture to afforestation in Heartwood Forest

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Introduction

The benefits of afforestation as mitigation for climate change and the promotion of biologically diverse wildlife communities are becoming increasingly recognised as having global importance (Berthrong *et al*., 2009; Malhi *et al*., 2002; Woodland Trust, 2011; Zanchi *et al*., 2007). As human urban populations and their demands on land and resources continue to grow, however, finding land suitable for afforestation is likely to become more difficult. Jørgensen and Fath (1998) noted that, despite an overall global rise in agricultural land (Benayas *et al*., 2007), between 1961 and 2002, the UK had the tenth highest continuous abandonment of agricultural land in the world. If this trend were to continue, it would leave a large amount of open land that may be useful for the implementation of afforestation projects. Inherently, however, agricultural methods have numerous, often negative impacts on soil quality (Kibblewhite *et al*., 2008). As a consequence, the resultant reduction in soil quality, or [the soil's] capacity to function (Karlen *et al*., 1997), could be seen as a potential driver for the rises seen in agricultural abandonment. It may be therefore that agricultural land abandoned for these reasons may not be suitable for afforestation (Flinn & Marks, 2007).

On completion, The Woodland Trust's Heartwood Forest project in Hertfordshire will be the largest new deciduous woodland in England. Some areas have only ceased use as agricultural land in the last couple of years. When fully mature, Heartwood Forest would be classified as a temperate deciduous forest, a habitat with vastly different soil quality requirements from the agricultural communities that were sustained on the land prior to the project's commencement. Care should be taken to ensure that the soil attributes at Heartwood Forest reflect those found within other established forests of this type within England (Schoenholtz *et al*., 2000).

Soil quality is a well-researched area of study and an abundance of information can be found on both woodland and agricultural soils. However, there is limited knowledge on how, what and when soil quality changes occur with a transition from agricultural land to woodland over time. As there is a high likelihood of further afforestation projects occurring on abandoned agricultural land in the UK in the future, it is crucial to achieve a robust understanding of what management techniques may need to be employed to ensure healthy woodland growth on and around altered and improved soils, if any.

This study provides analysis of parameters indicative of soil quality; pH (acidity/alkalinity), electrical conductivity (EC), soil organic matter (SOM) as well as earthworm surveys. The combination of these factors will help build an understanding of the soils found in three different habitats in Heartwood Forest, an area of unplanted agricultural land, recently planted woodland and ancient semi-natural woodland (ASNW). Comparisons will be drawn between these habitats to assess how soil quality has changed over time from being arable agricultural land, to how it may be when the woodland is fully established, whilst also providing a starting point for any continued monitoring of the site.

Site description

Heartwood Forest is a 347.22 ha area of ex-agricultural land, formerly known as Hill End Farm, purchased by the Woodland Trust in 2008; situated north of St Albans near Sandridge, within the Green Belt. The aim of the Heartwood Forest project is to create England's largest new deciduous woodland, with 600,000 trees planted over a ten year period, which, once mature, will provide connections between the areas of existing woodland (ASNW), found on the site and the nearby Nomansland Common to the north-east of the site (Figure 2). The predominant tree species planted include *Quercus robur* (Pedunculate Oak), *Fraxinus excelsior* (Ash) and *Carpinus betulus* (Hornbeam), with *Acer campestre* (Field Maple) and *Betula pendula* (Silver Birch) also featuring. Woody shrub species planted include *Corylus avellana* (Hazel), *Ilex aquifolium* (Holly), *Crataegus monogyna* (Common Hawthorn) and *Viburnum opulus* (Guelder Rose) (Woodland Trust, 2012; Smith, 2012).

The previous agricultural aspect of the land displays field patterns suggesting a 300+ year history as grade 3 arable, with likely crops being cereals, oilseed rape, beans and grass leys. The soils would have mostly been disturbed through ploughing and cultivation, with recent modifications by herbicide and pesticide use (Woodland Trust, 2009). Communications with the previous farm manager and subsequent desk study of the provided input/output data (1995-2012) from fields used as study sites showed extensive use of chemical additives to the soils whilst in production, including ammonium sulphate (21% N: 60% SO_4) based fertilisers and a wide array of herbicides, fungicides, insecticides and molluscicides. Typical N input ranged from 180-220 kg/ha, with SO_4 input ranging from 34.5-75 kg/ha depending on the field (K. Pearcy, 2013, pers. comm.: farm manager 1961-2012). The post-agricultural soils found on the Heartwood Forest site therefore provide a good comparable representation of the majority of agricultural soils across the UK.

In order to test soil quality changes between unplanted agricultural land and newly planted woodland over time, sample sites were selected that reflected habitats at progressive stages of afforestation (Figure 1). These were an unplanted area (*U*) that had been abandoned from agriculture in 2012 and left fallow but had not yet been planted with any trees (Plate 1) and a planted field (*P*) that had been planted with rooted whips (immature tree formed of a stem and small root system) two to three years before the samples were collected (Plate 2). Further samples were collected from a section of existing woodland (*W*) in order to compare what was found in habitats *U* and *P* to the possible eventual climax habitat of the site (Plate 3). In each habitat, five sample sites were used: the minimum amount per hectare as suggested by McRae (1988) (Figures 2, 3 & 4 and Table 1, GPS coordinates). It was necessary to select sample sites based on comparability with each other as well as ensuring that in each habitat only sample sites within the same geological profile ($h^{5'''}$; Upper Chalk) were selected (Figure 5).

Sampling strategy and analysis

From each sample site, five sub-samples were selected from a 20 × 20 m grid using a random number generator. Soil from the A-horizon was extracted using an auger to an amount of approximately 500 g soil (wet weight) as suggested by ICP-Forests (2010). The five sub-samples were mixed to form an homogenised composite sample. This was repeated for the five selected sample sites and for each habitat so that a total of 15 samples was collected. The samples were

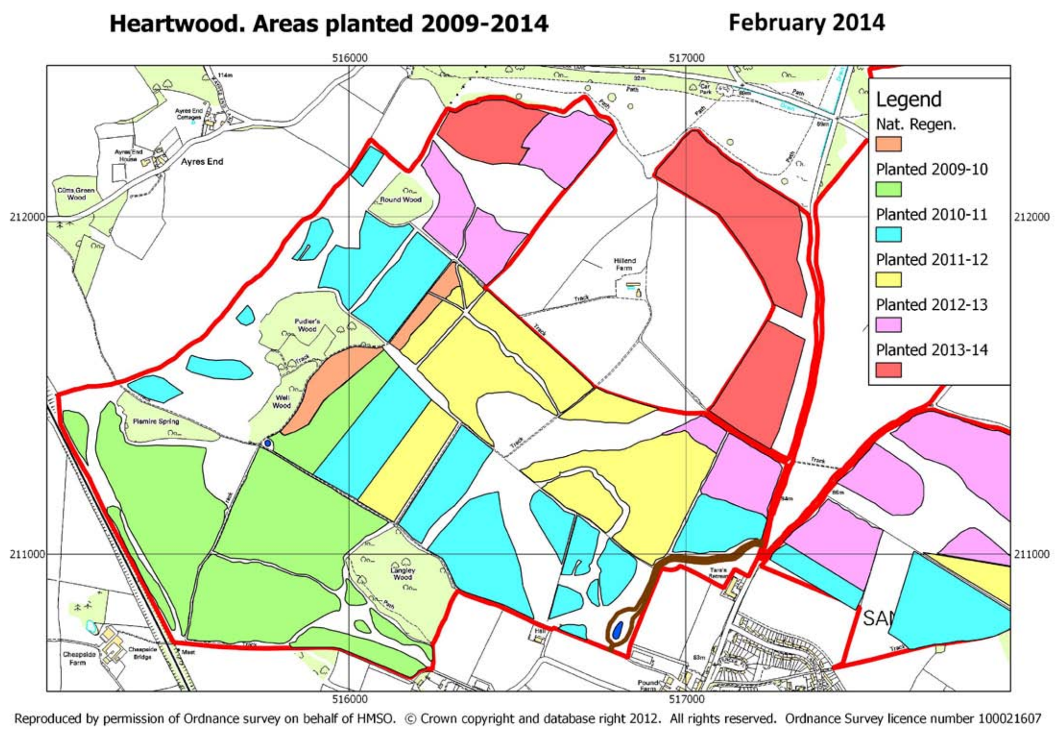

Figure 1. *Site map showing planting phases and dates for each section. Pale green areas are ancient woodlands – Pudler's Wood, Well Wood, Pismire Spring and Langley Wood, as well as the nearby Nomansland Common, with which Heartwood Forest will connect once fully developed (Source: Woodland Trust & Ordnance Survey).*

Plate 1. *View of the unplanted* (U) *habitat looking toward the Hill End Farm house in 2013.*

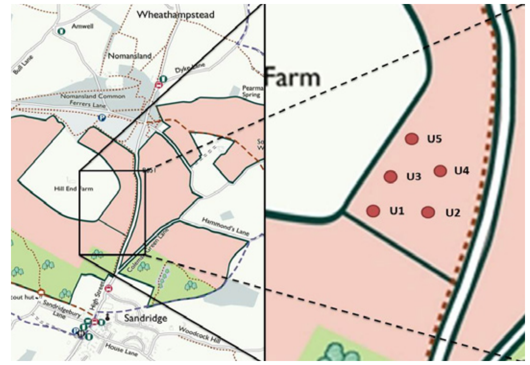

Figure 2. *Unplanted* (U) *habitat sample site locations. Locations are approximate and not to scale.*

Plate 2. *View across the recently planted* (P) *habitat in 2013. The planted 'rooted whips' can be seen in the foreground.*

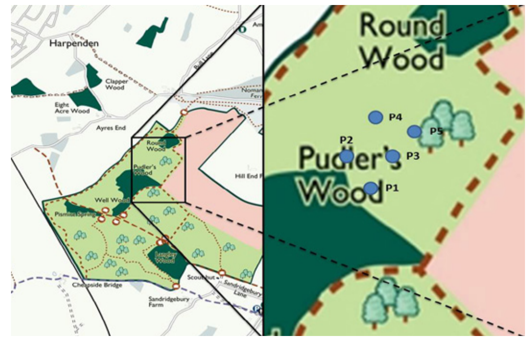

Figure 3. *Planted* (P) *habitat sample site locations.*

Plate 3. *An example of one of the woodland* (W) *sample sites in 2013. Sample sites with minimal trees, shrubs, fallen debris and footpaths were preferentially selected.*

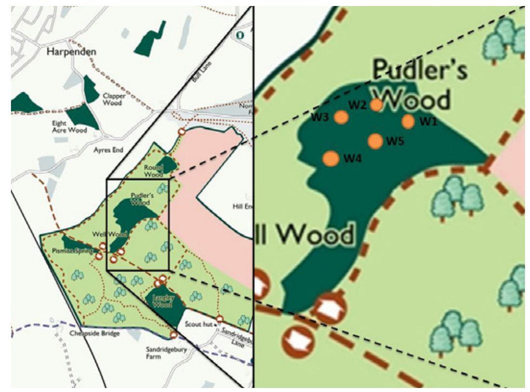

Figure 4. *Woodland* (W) *habitat sample site locations.*

Table 1. *Coordinates of the sample points, unplanted* U, *planted* P *and Woodland* W.

Unplanted		Planted		Woodland	
Sample ID	Coordinates	Sample ID	Coordinates	Sample ID	Coordinates
U1	TL17213 11401	P1	TL15995 11767	W1	TL15868 11761
U2	TL17275 11446	P2	TL15981 11791	W2	TL15865 11734
U3	TL17275 11534	P3	TL16025 11791	W3	TL15833 11697
U4	TL17317 11581	P4	TL16012 11827	W4	TL15862 11675
U5	TL17289 11652	P5	TL16060 11833	W5	TL15912 11666

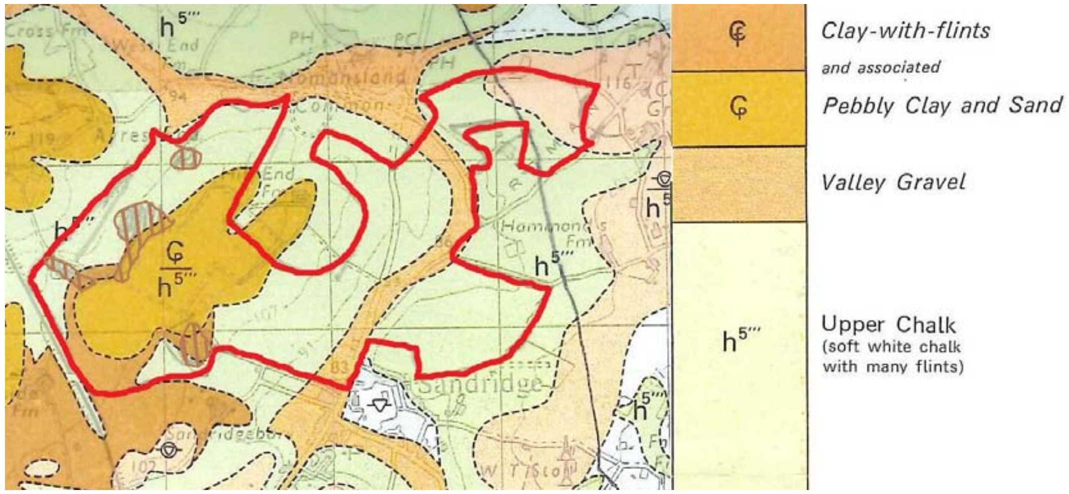

Figure 5. *Underlying geology of the Heartwood forest site with site boundary shown in red (Source: adapted from Ordnance Survey, 1978).*

tested for pH, and levels of electrical conductivity and soil organic matter, measured using the loss on ignition method.

Earthworm survey strategy

The earthworm survey was conducted during early spring (16 February-2 March, 2014), as time constraints meant that the temperature dropped below a suitable level for the earthworms to be active enough to survey at a similar time to the soil sampling. It was completed over two weeks under weather conditions and temperatures comparable to the times for the soil sampling. Using the same sample sites as those used for the soil sample extraction, the GPS coordinates were used to locate the central point of the 20 × 20 m quadrat. The procedure used for the survey followed those outlined in the OPAL soil and earthworm survey guide (OPAL, 2014).

Plate 4. *An example of an earthworm survey pit (left) and extracted soil for sorting through (right) in the woodland (W) habitat.*

Results

pH

The soils in habitat *W* showed the most acidic mean pH value (Figure 6). An analysis of variance (ANOVA) displayed a significant difference between the habitats ($F_{2, 12} = 29.784$, $p < 0.001$). Tukey's HSD Post-hoc Test showed a significant difference between habitats

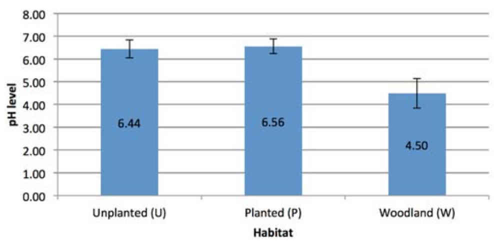

Figure 6. *Mean pH levels of the three habitats, with error bars showing standard deviation. Significant differences were found between habitats* P – W *and* U – W, *(Tukey's HSD, p < 0.05).*

P – W. Similarly, a significant difference was calculated between habitats *U – W*. No significant difference was found between habitats *U – P* (p = 0.05).

Electrical conductivity

The lowest mean EC level was observed in habitat *U* and habitat *W* the highest (Figure 7). An ANOVA calculated no significant difference between any of the three habitats ($F_{2, 12} = 0.774$, $p = 0.483$). The data set with the biggest range between minimum and maximum values was that of habitat *W*.

Soil organic matter

The highest organic matter levels were measured in

Table 2. *Adult and immature earthworm abundance observed in the three habitats. Habitat* U *and* P *showed significant differences in earthworm frequency compared with habitat* W *for both immature and adult earthworms, (Kruskal-Wallis, p < 0.05).*

Earthworm species	Overall abundance (per 0.02 m³)		
	Woodland (W)	Planted (P)	Unplanted (U)
Aporrectodea caliginosa	0	7	8
Allolobophora chlorotica (green form)	0	2	10
Allolobophora chlorotica (pale form)	0	0	1
Eisenia fetida	0	1	0
Lumbricus terrestris	0	0	2
Octolasion cyaneum	0	0	4
Aporrectodea rosea	0	0	3
Total immatures	0	91	21
Total adults	0	10	28
Total worms	0	101	49
Total species	0	3	6

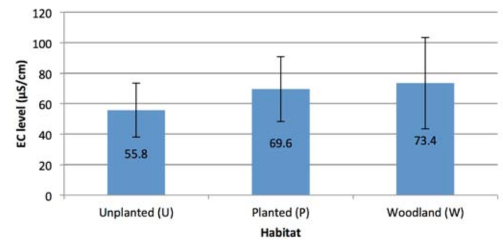

Figure 7. *Mean electrical conductivity (EC) levels of the three habitats. Error bars show standard deviation.*

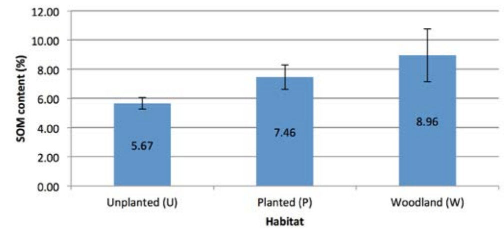

Figure 8. *Mean percentage levels of soil organic matter (SOM) found in each habitat with error bars showing standard deviation. Significant differences were found between habitats U and W (Tukey's HSD, p < 0.05).*

habitat *W* (Figure 8). An ANOVA test calculated a significant difference between the habitats ($F_{2, 12} = 9.817$, $p < 0.003$). Tukey's HSD Post-hoc test showed that there was a significant difference between habitats *U – W* (p < 0.05). No significant difference was found in comparisons between the other habitats.

Earthworms

Of the two dozen species of earthworm found in Britain, seven were identified at Heartwood Forest at the time of the surveys. The highest total abundance of earthworms was found in habitat *P*, with 91 immature and 10 adult earthworms found over five surveys. The highest abundance of adult earthworms, however, was found in habitat *U*, where 28 adults were found, with only 21 immature. No earthworms of either immature or adult stage were found in habitat *W* (Table 2). As only mature earthworms are identified to species level, due to the difficulty of identifying immature specimens (Sims & Gerard, 1999), the habitat with the highest number of identifiable worms was habitat *U*, which also showed the highest diversity (six different species were identified in habitat *U* compared with three in habitat *P*) .

The species found in the highest abundance overall was *Aporrectodea caliginosa*, which was found in almost equal abundance in habitats *U* and *P*, with seven in *P* and eight in *U*. The second most abundant species was *Allolobophora chlorotica* in both its green and pale forms. A total of 13 specimens was found over all the habitats, with 11 in habitat *U*. The species with the lowest abundance was *Eisenia fetida*, with only one specimen in habitat P and nowhere else.

A Kruskal-Wallis test was used to test for variance due to non-parametric data. This showed there was a significant difference between habitats *U – W* and *P – W* for both immature and adult earthworm populations (p < 0.05).

Discussion

Perhaps unsurprisingly, habitat *U* displayed very little in the way of ground flora or grasses present at the time of study (Plate 1), especially in comparison with habitat *P*, which showed an observable abundance of grasses and other forbs (herbaceous plants) (Plate 2). Dead plant matter was noted to be present, which was likely to be of agricultural origin, since the field was in production at least until 2012. Communications with the previous manager of Hill End Farm revealed that, for the production year 2011/12, the crop grown on this habitat site was Solstice wheat. He had no involvement in the management of the field used for this habitat study by this time, however, and so could not say for certain, but assumed that 220 kg N/ha were applied to the field along with 62.5 kg 21% N: 60% SO_4/ha (ammonium sulphate based fertiliser product) and a similar pesticide application strategy to the rest of the site (K. Pearcy, 2013, pers. comm.). Agricultural input and output data were not known for the following year.

pH

One of the most influential factors affecting and similarly *affected* by soil quality is pH (Lukac & Godbold, 2011; Moffat, 2003). High acidity, for example, can have a restricting effect on the growth and development of root systems for many plant species, mainly due to increased solubility and toxicity of aluminium in acidic conditions (Ashman & Geeta, 2002; Binkley & Fisher, 2013). Organically loaded woodland soils, however, do typically display a more acidic pH, exceptions being those that feature a high concentration of calcareous underlying geology, which can reach alkaline pH levels of around 8.0 (Forestry Commission, 2011; Lukac & Godbold, 2011). Due to the naturally acidic nature of precipitation (a product of the dissolution of CO_2 with atmospheric water vapour to form carbonic acid), soils are more commonly slightly acidic regardless of what is growing upon them (Lukac & Godbold, 2011). However, where woodland is developing on post-agricultural land, soil acidity tends to increase as SOM, C and N accumulate (Flinn & Marks, 2007). The soils sampled for this research were all taken from habitats overlying calcareous geology (Figure 8); however, the past agricultural aspect of the site with added chemical soil improvements may well have had neutralising effects on the soils. It was expected that acidity would increase, with habitat *U* showing the least acidic mean pH and habitat *W* showing the most acidic conditions, but that the soils may show a more alkaline pH than other habitats of this type due to the calcareous nature of the underlying geology. The mean pH values observed in the soil samples taken from Heartwood Forest indicate the expected increasing tendency towards acidity from agriculture to woodland, as described by Flinn and Marks (2007), with habitats *U* and *P* displaying a significantly higher pH than that of *W*.

Electrical conductivity (EC)

Electrical conductivity gives an understanding of the nutrient transport and availability of a soil by measuring the amount of soluble salts, whereas the higher the electrical conductivity; the higher the concentration of salts. It is generally understood to be the most important water quality parameter with regard to irrigation, as it can affect the pH balance of the soil, the ability of plants to absorb water and nutrients, whilst high alkalinity (associated with high salt content) can cause organic matter dispersal and therefore has a direct effect on the texture and overall quality of the soil. Tolerance levels to soil salinity vary greatly between plant species and tolerance tends to increase with maturity. Whilst small amounts of soluble salts are important to the health of a soil and nutrient uptake of plants, in situations of poor drainage and aeration the concentrations can accumulate to toxic levels, with concentrations above 4-8 dS/m (400,000-800,000 µS/cm) proving too high for many plants and 0-2 dS/m (0-200,000 µS/cm) being favourable for most plants. Soils with higher clay content have an increased ability to retain water and therefore are more susceptible to detrimental concentrations of salts (Gerard, 2000; Keren, 2000; Miller & Gardiner, 1998).

All three habitats on the Heartwood Forest site yielded EC levels below the thresholds known to be unfavourable for healthy plant growth and within the low soil salinity range given by Miller and Gardiner (1998). The mean EC observed in habitat *U* was 55. 8 µS/cm, the lowest value of the three habitats, which suggests it has the lowest capacity for nutrient transport and availability. The lower EC values found in this habitat are expected for soils with lower acidity, as a higher salt content can lead to more alkaline conditions in the soil (McRae, 1988). The highest mean EC level was found in habitat *W* (73.4 µS/cm). This could be attributed to the slightly higher clay content of the soils found here. The underlying calcareous geology in this respect does not seem to have had a noticeable effect on the overall alkalinity and EC of the habitats. As all EC levels are well below what would be considered unfavourable to plant growth and the maturity of the woodland (400+ years old) it is unlikely this would pose any direct problem to the woodland or to the newly planted areas as they develop. Further, with the gradual increase in EC seen from the agricultural soils compared with the ancient woodland in only a few years, it is possible that the EC of habitats *U* and *P* will achieve a similar level to that of habitat *W* within only a few more years of growth. It may be that levels end up surpassing those found in habitat *W*. However, this would need to be confirmed with further monitoring.

Soil organic matter (SOM)

Levels of organic matter play a role in virtually all soil functions. It is the main store of carbon (the main constituent element of all flora and fauna (around 45% in plants) within soils (Sakrabani *et al*., 2012). In terms of pH, the accumulation of organic matter will lead to higher levels of acidity (Bloom, 2000), increased nutrient content (such as N, P and K) and cycling (Binkley & Fisher, 2013 Kibblewhite *et al*., 2008; McLauchlan *et al*., 2006). It can indicate lower concentrations of soluble salts (Gerard, 2000) and greater abundances of earthworms (Kibblewhite *et al*., 2008; Sims & Gerard, 1999). Evidently, therefore the organic matter content of a soil is a critical indicator of its overall health. Boatman *et al*. (2007) note that inorganic fertilisers typically used on agricultural soils reduce the amount of organic matter present. Furthermore, the harvesting of crops from arable agricultural land inherently removes a large amount of organic material that in non-agricultural habitats would usually be left to decompose back in to the soil, continuing the nutrient cycle. For this reason, woodland soils, especially ASNW, have a high SOM content (Forestry Commission, 2011). It was expected, therefore, that habitats *U* and *P* would yield the lowest SOM values (*U* showing the lowest), with habitat W having the highest observable SOM content.

This was borne out by the results; with habitat *U* showing the least mean % SOM (5.67), habitat *P* showing the second highest (7.46) and habitat *W* showing the most (8.96). The only significant difference was found between habitats *U* – *W*, which gives an indication of the short amount of time it takes to replenish SOM content. This result is supported by McLauchlan *et al*.'s (2006) findings, which suggest that in habitats converted from agriculture to grassland, SOM and associated nutrients, mainly carbon, build up in decadal timescales, reaching a maximum within 55-75 years. Considering habitat *P* had been planted a mere two years prior to testing and was already showing SOM levels that were statistically insignificantly different from habitat *W*, it can be expected, assuming habitat *P* had a SOM content similar to habitat *U* before planting, that either this rate of increase will begin to slow until it is at a more comparable level to habitat *W* or that it will surpass levels found in habitat *W*, if only temporarily, until an equilibrium is reached. This can only be known if further monitoring were to be continued on the site.

The SOM of the samples for this research was determined using the 'loss on ignition' method, which involves burning off the carbon content of the soil sample at high temperatures and measuring the weight difference before and after ignition. It is noted by McRae (1988), however, that this method can produce erroneous results. This is due to weight being lost from the conversion of free $CaCO_3$ in the soil to CaO. This can be corrected for if the amount of $CaCO_3$ is known prior to testing. Further losses in weight can be due to dehydration of amorphous oxides and clay minerals (McRae, 1988). Due to the calcareous underlying geology and clay content of the sample sites used, future monitoring of the site should take this factor into account when determining SOM levels and a more robust method of analysis would be preferable.

Earthworms

Earthworms are frequently considered to be some of the most important of all soil fauna due to the amount of essential physical and chemical processes to which they actively contribute. Binkley and Fisher (2013) suggest the optimum soil pH for most earthworms to be between pH 6.0-8.0. Although acidic soils can often support earthworm populations they are rarely found in soils with a pH <4.5 (Gerard, 2000). Furthermore, Hooker and Compton (2003) observed that few worms were found in woodland stands >60 years old. Due to the expected acidity of the woodland soils and the age of the ASNW, as well as previous surveys done on the Heartwood Forest site, which found only a single earthworm in the woodland (Shah, 2012), there was little expectation of finding many specimens in habitat *W*. This is reflected in the results, with no specimens being found at all in habitat *W* and significantly more observed in *P* and *U*. This finding corresponds further with Binkley and Fisher's (2013) assertion that in acidic forest soils, it is often fungi that fill the role of major decomposers. It is possible that seasonal differences in climate and soil quality may have played some role in the lack of any earthworms in *W*. However, the mean pH of the habitat (pH 4.5) is likely to have been the biggest contributor. This would need to be addressed by further surveys.

The two most abundant species found in the other two habitats, *A. caliginosa* and *A. chlorotica*, are noted by Sims and Gerard (1999) to have lifecycles particularly affected by seasonal changes in temperature and soil moisture content. They state that embryonic development for these species is arrested immediately when egg capsules are subjected to temperatures below 5°C. Assuming adequate soil moisture, *A. chlorotica* juveniles will emerge after 36 days when the temperature reaches 20°C, to 119 days at a temperature of 10°C. Prior to the time of sampling (16February-2 March, 2014), the UK had seen record winter rainfall and relative absence of low temperatures (Met. Office, 2014). This unusual weather may have contributed to the high abundance of juveniles found in habitats *U* and *P*. It may have been beneficial to include soil moisture content as a further parameter for analysis in this study, as this would have given an indication of soil drainage capacity and nutrient leaching, important factors in assessing the suitability of the soil to support earthworms.

It is an interesting point to note that the highest abundance of juveniles was found in habitat *P* whilst *U* displayed a higher abundance of adults. Some species of earthworm can live as long as 30 years in favourable conditions, with *A. chlorotica* reaching maturity after 17-19 weeks (Sims & Gerard, 1999). This suggests that, although at the time of surveying habitat *P* contained more identifiable adult specimens than habitat *U*, within a few months it is likely that habitat *P* will overtake *U*, to yield a more robust assemblage of mature earthworms. Again, this would need to be assessed with further surveys. The previous study of earthworm assemblages in Heartwood Forest by Shah (2012) found *Lumbricus terrestris* to be the most abundant on site. The difference could be attributable to the time of year the study was conducted, Shah's in autumn, this study's in early spring. It may also be due to changes in soil quality since 2012. Further monitoring of the site may provide some more clarity on the discrepancies found between the two studies.

Conclusion

This study has provided a baseline assessment of a number of soil quality variables across three different habitats found at Heartwood Forest. The three habitats used in the study were selected to provide a basic understanding of how the land was prior to the study (unplanted post-agricultural land – habitat *U*), how the majority of the site is currently (recently planted woodland – habitat *P*) and the possible eventual climax habitat of the site (ASNW – habitat *W*). Prior to sample collection and analysis and earthworm surveys, desk study and personal communications with the previous land manager provided contextual knowledge on past land management practices on the site. This showed extensive agro-chemical and fertiliser applications typical of an arable farm of this type in the UK for at least the last 10 years.

Analyses of soil samples showed that, overall, soil quality appears to be developing and improving from post-agricultural land to woodland, with EC levels seen to show a closer relation between recently planted woodland and ASNW. Currently, however, the recently planted soils were still quite different from the ASNW soils. Soil pH was found to be marginally higher in habitat *P* than *U*, but still significantly different from *W*. Whether this is a successional response to increased grass cover, higher abundance of earthworms, anomalous outliers in samples collected, or possibly several other factors cannot be said for certain without further monitoring. Earthworm abundance was higher in habitat *P*, showing that soil conditions for this habitat are presently more favourable than the unplanted ex-agricultural habitat. A possible link can be seen here with the higher levels of SOM, a factor likely to increase as the woodland develops over time.

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References

Ashman, M. & Geeta, P. (2002). *Essential soil science: a clear and concise introduction to soil science.* Oxford: Blackwell Publishing.

Benayas, J. M. R., Martins, A., Nicolau, J. M & Schulz, J. J. (2007). 'Abandonment of agricultural land: an overview of drivers and consequences'. *CAB Reviews: Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources*, 2(57).

Berthrong, S. T., Jobbagy, E. G. & Jackson, R. B. (2009). 'A global meta-analysis of soil exchangeable cations, pH, carbon, and nitrogen with afforestation'. *Ecological Applications*, 19(8): 2228-2241.

Binkley, D. & Fisher, R. F. (2013). *Ecology and management of forest soils.* (4th ed.). Chichester: Wiley-Blackwell.

Bloom, P. R. (2000). 'Soil pH and pH buffering'. In: M. E. Sumner (ed.), *Handbook of soil science*. (pp. B-333-B-352). Boca Raton: CRC Press LLC.

Boatman, N. D., Parry, H. R, Bishop, J. D. & Cuthbertson, A. G. S. (2007). 'Impacts of agricultural change on farmland biodiversity in the UK'. In: R. E. Heston & R. M. Harrison (eds.), *Biodiversity under threat.* (pp. 1-32). London: Royal Society of Chemistry.

Flinn, K. M. & Marks, P. L. (2007). 'Agricultural legacies in forest environments: tree communities, soil properties, and light availability'. *Ecological Applications*, 17(2): 452-463.

Forestry Commission (2011). *Forests and soil: UK forestry standard guidelines*. Edinburgh: Forestry Commission.

Gerard, J. (2000). *Fundamentals of soils*. London: Taylor & Francis Ltd.

Hooker, T. D. & Compton, J. E. (2003). 'Forest ecosystem carbon and nitrogen accumulation during the first century after agricultural abandonment'. *Ecological Applications*, 13(2): 299-313.

ICP-Forests. (2010). Part X – 'Sampling and analysis of soil'. *Manual on methods and criteria for harmonized sampling, assessment, monitoring and analysis of the effects of air pollution on forests.* Hamburg: UNECE.

Jørgensen, S. E. & Fath, B. D. (2008). 'Agriculture'. *Encyclopedia of ecology*. Oxford: Elsevier.

Karlen, D. L., Mausbach, M. J., Doran, J. W., Cline, R. G, Harris, R. F. & Schuman, G. E. (1997). 'Soil quality: a concept, definition, and framework for evaluation (guest editorial)'. *Soil Science Society of America Journal*, 61(1): 4-10.

Keren, R. (2000). 'Salinity'. In: M. E. Sumner (ed.), *Handbook of soil science*. (pp. G-3-G-25). Boca Raton: CRC Press LLC.

Kibblewhite, M. G., Ritz, K. & Swift, M. J. (2008). 'Soil health in agricultural systems'. *Philosophical Transactions: Biological Sciences*, 363(1492): 685-701.

Lukac, M. & Godbold, D. L. (2011). *Soil ecology in northern forests: a below ground view of a changing world.* Cambridge: Cambridge University Press.

Malhi, Y., Meir, P. & Brown, S. (2002). 'Forests, carbon and global climate'. *Philosophical Transactions: Mathematical, Physical and Engineering Sciences*, 360 (1797): 1567-1591.

McLauchlan, K. K., Hobbie, S. E. & Post, W. M. (2006). 'Conversion from agriculture to grassland builds soil organic matter on decadal timescales'. *Ecological Applications*, 16(1): 143-153.

McRae, S. G. (1988). *Practical pedology: studying soils in the field.* Chichester: Ellis Horwood Ltd.

Met. Office (2014). 'Winter storms, January to February 2014'. *Past Weather Events*. Retrieved March 15, 2014, from http://www.metoffice.gov.uk/climate/uk/interesting/2014-janwind

Miller, R. W. & Gardiner, D. T. (1998). *Soils in our environment*. (8th ed.). New Jersey: Prentice-Hall.

Moffat, A. J. (2003). 'Indicators of soil quality for UK forestry'. *Forestry*, 76(5): 547-568.

OPAL (2014). *Soil and earthworm survey*. Retrieved March 6, 2014 from http://www.opalexplorenature.org/Earthwormguide

Osman, K. T. (2013). *Soils: principles, properties and management*. London: Springer.

Sakrabani, R., Deeks, L. K., Kibblewhite, M. G. & Ritz, K. (2012). 'Impacts of agriculture upon soil quality'. In: R. M. Harrison, R. E. Hester & J. Morris (eds.). *Environmental impacts of modern agriculture.* (pp. 35-56). Cambridge: RSC.

Schoenholtz, S. H., Van Miegroet, H. & Burger, J. A. (2000). 'A review of chemical and physical properties as indicators of forest soil quality: challenges and opportunities'. *Forest Ecology and Management*, 138: 335-356.

Shah, K. (2012). *Exploring the relationship between contrasting habitats and earthworms at Heartwood Forest, Hertfordshire.* Unpublished undergraduate dissertation, University of Hertfordshire, Hatfield.

Sims, R. W. & Gerard, B. M. (1999). *Earthworms*. Shrewsbury: Field Studies Council.

Smith, L., Gravestock, L., Legg, B., Moss, J., Mowe, J., Shortall, C., Smith, K., Steele, A., & Wight, T. (2012). 'Long-term monitoring at Heartwood Forest'. The *Hertfordshire Naturalist: Trans. Hertfordshire Nat. Hist. Soc.*, 41(1): 56-67.

Woodland Trust (2009). 'Soils, air and water'. *Heartwood Forest Environmental Impact Assessment*. Grantham: Woodland Trust.

Woodland Trust (2011). *The state of the UK's forests, woods and trees: perspectives from the sector*. Grantham: Woodland Trust.

Woodland Trust (2012). *Heartwood Forest: management plan 2012-2017*. Grantham: Woodland Trust.

Zanchi, G., Thiel, D., Green, T. & Lindner, M. (2007). *Afforestation in Europe.* Joensuu: European Forest Institute.

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