European Innovation Partnership (EIP) Wales

Comparison of the relative environmental benefits of low impact machinery in small scale woodlands

Full report

September 2019

ADAS GENERAL NOTES

Project No.: 1020716

Title: Comparison of the relative environmental benefits of low impact machinery in small scale woodlands

Client: Welsh Government / EIP5 Wales

Office: **Wolverhampton**

Status: Final

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Menter a Busnes delivers the EIP Wales scheme on behalf of the Welsh Government, and has received funding through the Welsh Government Rural Communities – Rural Development Programme 2014-2020, which is funded by the European Agricultural Fund for Rural Development and the Welsh Government.

For Welsh farm and forestry businesses to remain competitive, profitable and resilient, they will need to work on a continuous programme of improving both business and technical practices.

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EIP Operational group

The businesses represented in the operational group are:

Organisation	Name	Farm	Role
	Michael Lewis	Meadow View, Cowbridge	Lead Farmer/Forester & principle contact
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Other members of the project

	J.V. Tree Services		Forestry Contractors
RSK ADAS Ltd	Aldwyn Clarke Jason Stopps Lorna Johnson Steven Anthony	Canolafan Enterprise Park Llanafan Ceredigion SY23 4AY	Scientists procured to carry out the research
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EXECUTIVE SUMMARY

Small woodlands in Wales are currently an undermanaged resource. If these woodlands could be brought back into management by landowners, they could provide a valuable source of extra revenue. Although not all of the woodland products would be suitable for the timber market, collectively small woodlands present an opportunity for increased timber production in Wales, which at present is very desirable given the increase in timber demand. Managing small woodlands will also benefit woodland ecology and support the provision of ecosystem services provided by the woodland environment (e.g. clean air, biodiversity, climate regulation (carbon sequestration) and flood alleviation). However, the cost of conventional machinery used for timber operations is not economically viable to smaller landowners. Furthermore timber operations can be damaging to soils and water if the machinery is not suited to the site, or operations are carried out inappropriately. Thus, the correct machinery choices must be made to reduce the risk of environmental damage, but they must also be feasible for the landowner.

The following study aimed to highlight the issue of soil and water management during forest operations by investigating the use of low impact machinery on soil structure and runoff in smaller woodland parcels. Two eligible woodland sites were identified based on their uniformity in surface and subsurface site conditions (such as soil type, slope, stand density and rainfall). The woodlands were undermanaged and it was recognised that reinstating management could bring benefits in terms of wildlife and amenity value and firewood. The project sought to quantify the volume of water and sediment concentration losses from four treatment areas, including a Control treatment (no activity will take place), conventional harvesting treatment, and two low-impact forestry treatments using an Alpine tractor and a tracked harvester vehicle. Post-treatment runoff volumes, nutrient concentrations of runoff and soil structure (compared against baseline studies) were assessed to investigate the impact of treatments.

Results from the project showed that soil structure did not appear to change significantly post-treatment and runoff volume and nutrient concentrations did not appear distinctly different between treatment plots. This may have been due to the impacts of extraneous variables such as natural drainage channels. However, the study was useful in highlighting the issue of soil and water management during forest operations and did show that the low impact equipment was as capable at clearing small woodland rides as the conventional machinery and did not cause lasting impacts on the soil structure.

Future studies would benefit from more replicates and passes with machinery, potentially including horse extraction, to identify if there is any significant differences between machinery types and an economic feasibility study on low impact machinery could be useful. In future research more sensitive soil variables should be taken into account when assessing the effect of machinery on soil compaction. Organic matter levels could also be measured post-treatment to compare with baseline results as forest machinery can cause organic matter deficiencies.

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1 INTRODUCTION

There are 0.3 million hectares of woodland in Wales (10% of total UK woodland cover) (Vanguelova *et al.,* not dated*).* To deliver the Woodlands for Wales Strategy successfully, Welsh woodlands need to be sustainably and actively managed. Bringing more woodlands (including the smaller parcels) into active management in line with UKFS (UK Forestry Standards) is one of the first steps to delivering the Welsh woodland strategy. Farmers in particular, are being encouraged to bring their native and ancient farm woods into formal and sustainable management (Welsh Government, 2019). Forest management machinery needs to be selected based on the following conditions of the site; slope, ground roughness, access and network distance, tree size and produce size (Saunders, 2015). In more recent decades, manual felling and logging by animals or small tractors has become less frequent. Instead, mechanized harvesting with heavy tractors or specialized forestry machinery has been more frequently utilised since the beginning of the 20th century. Forestry machinery now includes: harvesters, forwarders, skidders, feller-bunchers and knuckleboom loaders (Ampoorter, 2011). Unfortunately, the disproportionate cost of large forestry machinery to manage and harvest a small amount of trees is one of the reasons many small woodlands in Wales are neglected. In addition, larger machinery can be environmentally damaging to woodlands, though some of the newer forwarders have been designed with tracks, improving their ability to extract timber without causing disturbance in environmentally sensitive areas. Site disturbance caused by some heavy machinery (typically 12-14 tonnes in an unloaded state) can result in degradation of soil properties (Ampoorter, 2011). It can also affect water flow and degrade the quality of water in the forest and downstream. Some machines are capable of leaving deep ruts in the soil and causing compaction, consequently increasing the risk of flooding and sediment delivery. A reduction in soil function and water quality accordingly prevents the provision of ecosystem services (Moffat, 2003).

Low impact machinery could be an economically and environmentally viable option to increasing small scale woodland management. Adapted agricultural machinery can also be well suited to managing small woodlands as well as being economically attractive (Saunders 2015). Two farmers in the Vale of Glamorgan are facing problems accessing their farm woodlands and wanted to conduct an investigation to assess the effect of low impact machinery. The two farmers, alongside 'Actors' Ian Nicholas a woodland consultant who developed the woodland management plan for one of the woodlands, and Nigel Elgar Catchment officer for Welsh Water constitute the operational group for the project. The following study will investigate the benefits of machinery, including an articulated Alpine tractor and machinery with tracked skid steers, to identify more appropriate methods of minimising environmental disturbance. Increasing the management of timber resources with more appropriate machinery could provide the landowner with another stream of revenue as well as improving the woodland ecosystem and ecology. Protecting the ground during operations also safeguards it for future use (Saunders, 2015). One of the Actors in this project, Welsh Water, noted that 'nearly all the potential issues with forestry harvesting revolve around soil management – turbidity, colour, carbon, potential nutrients and metals (depending on soil status). In severe cases turbidity will prevent any processing of drinking water for an extended period'. Farm woodland owners in Wales must also be aware of the Codes of Good Agricultural Practice and GAEC 5 in particular: Soil and Carbon Stock - Minimum land management site specific conditions to limit erosion.

Policy also requires proper soil and water management. The UK is a participant in long-standing international frameworks aimed at the protection of soil. These include the FAO World Soil Charter, 1992 UN Conference on Environment and Development, the UNCBD, and the Forest Europe process. The principal frameworks protecting water include; the EU Water Framework Directive, adopted in 2000, and Forest Europe. Forest Europe requires the UK to maintain and enhance the protective functions of forests for water and soil (Forestry Commission, 2017).

1.1 Introduction to the Sites

1.1.1 Coed y Ddulluan

Coed y Ddulluan is one of the two woodlands utilised during this research. It is a small scale (12 ha), mixed commercial site, located near Cardiff (see Figures 1 and 2). The owner runs a firewood business from the site. The woodland has previously been thinned, however difficult access has hampered operations and the firewood business is not currently operating, despite demand. Within the woodland a relatively uniform area was located in terms of tree type, cover/density (See Figure 3) and slope (around 15%). The area has an existing hard standing track on the bottom, top and right-hand side (see Figures 4 and 5). The location prevents any interference from other work which may be carried out above the area by the owner/contractor.

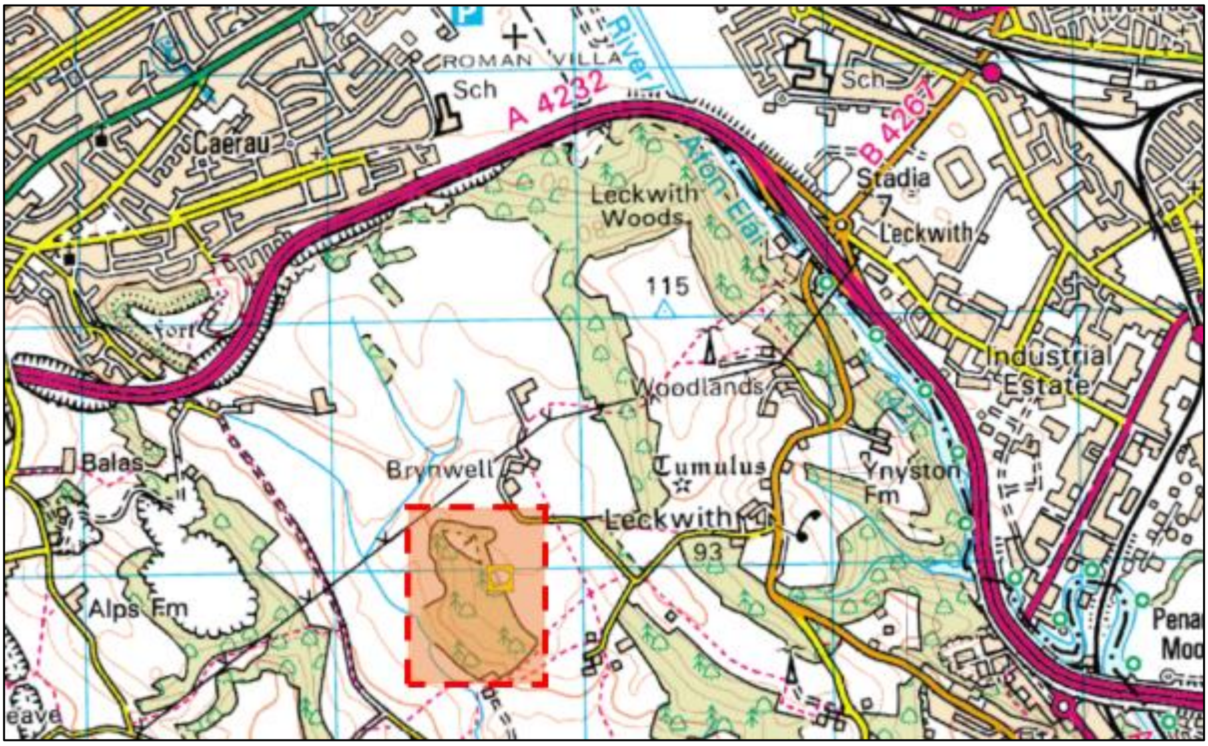

Figure 1 Location of Coed y Ddulluan

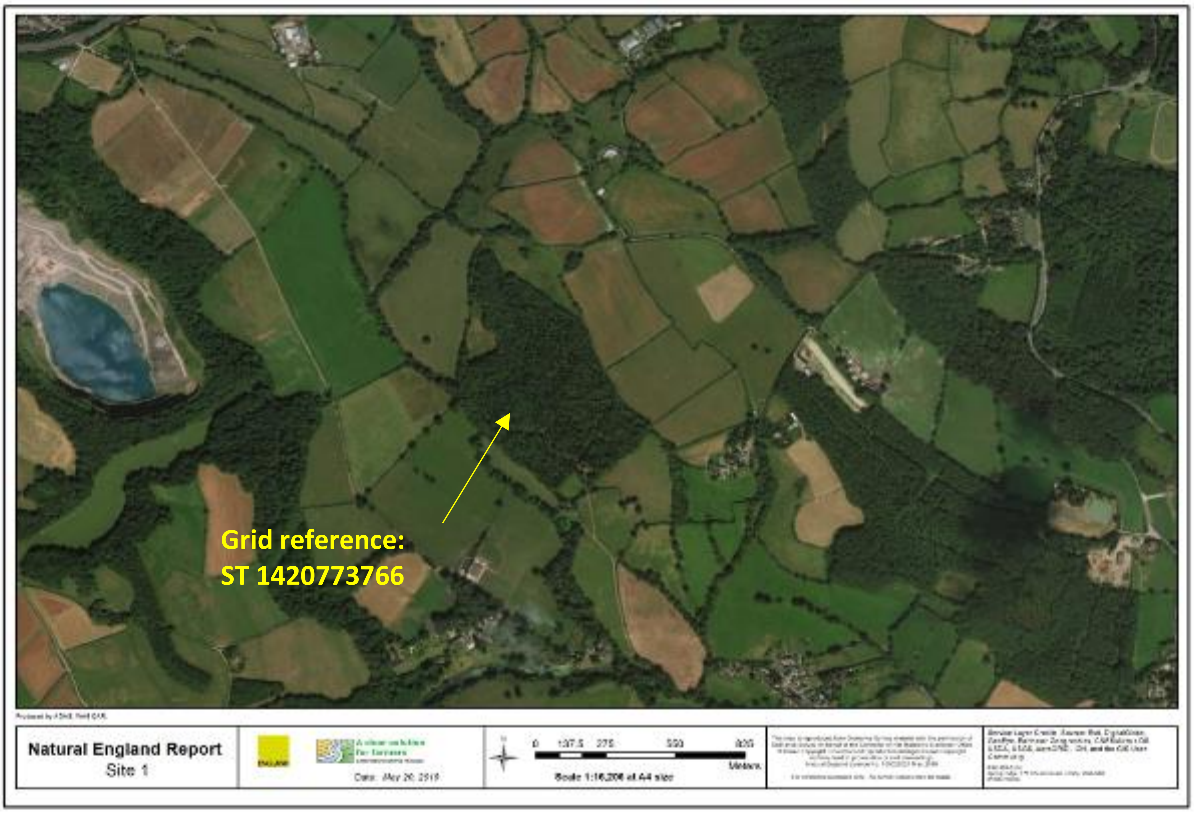

Figure 2 Aerial imagery of Coed y Ddulluan

Figure 3 Canopy structure of Coed y Ddulluan

Figure 4 Top track in Coed y Ddulluan

Figure 5 Bottom track in Coed y Ddulluan

1.1.2 New Breach

The second site, New Breach, is a 0.6-0.8 ha broadleaved woodland near Cowbridge and is utilised as an amenity woodland (see Figures 6 and 7). This site differs slightly to Coed y Ddulluan in that there is an existing, very over grown green byway type road running along the bottom of the site. The woodland is made up of large hardwood trees and unmanaged hazel coppice understory and slope is around 10% (see Figures 8 and 9). The upper edge of the woodland is bordered by grassland.

Figure 6 Location of New Breach woodland

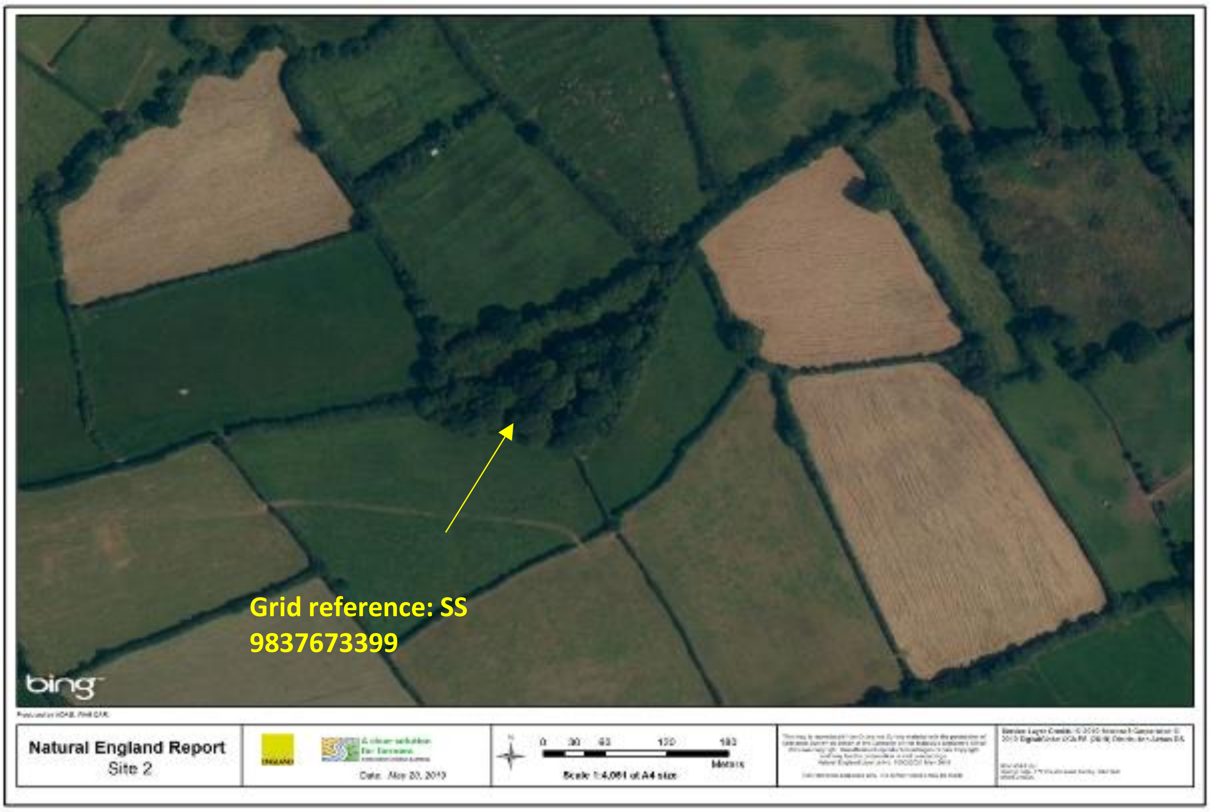

Figure 7 Aerial imagery of Coed y Ddulluan

Figure 8 Canopy structure of New Breach woodland

Figure 9 Canopy structure of New Breach woodland

1.1.3 Baseline Surveys

Topographical observations made and soil samples which were collected and analysed as part of the baseline data gathering, indicated that both sites were found to be similar in texture (clay based), slope (10 and 15%), organic matter content (OM) and both have low stone contents. The bulk density (BD) was also assessed in each treatment ride of both woodlands. BD was higher in all subsoil samples compared to topsoil samples (see Figure 10). This is as expected due to the high level of OM found in the topsoil (see Figure 11). The topsoil had an average OM of 13.175 % w/w and the subsoil had an average of 5.15 % w/w. Forest soils naturally have high levels of organic or carbon content in comparison to grassland and cropland forest topsoil. This is due to their well-developed organic matter layers and higher organic matter content, created from forest litter which is incorporated into the topsoil by microorganisms (Vanguelova *et al.,* Not dated; Forestry Commission, 2017). The average topsoil BD was 0.7 g/cm^3 which is a typical topsoil BD content for broadleaved woodlands according to the Countryside Survey which gave a figure of 0.78 g/cm^3 for the Broad Habitat Classification “Broadleaved, Mixed and Yew Woodland”. The minimum BD content found was 0.61 g/cm^3 and max was 0.82 g/cm^3. Soils with higher OM usually show lower BDs as lower organic matter content decreases the stability of soil aggregation and decreases pore size and therefore increases BD. Thus, topsoil BDs should be lower than subsoil BDs in this instance.

Visual assessments were carried out on all treatment sites using the BioAgriNomics Visual Soil Assessment (VSA) tool (for topsoil) (Sheperd, 2000) and Visual Evaluation for Soil Structure (VESS) (for subsoil). None of the results were above moderate to poor quality in either woodland making them suitable sites to compare in term of their soil structure. Results from the topsoil assessments found that 25% of soil pits had poor soil quality in Coed y Ddulluan and 8% of soil pits in New Breach had poor topsoil. The remainder (75 % in Coed y Ddulluan and 92% in New Breach) were categorised as having moderate quality soil (Guimaraes *et al.,* 2011). Subsoil soil assessments indicate that 100% of soil pits in Coed y

Ddulluan were poor quality, similarly in New Breach 92% of subsoil pits were in a poor state. Forests have traditionally been planted on sites with lower soil quality if they were not valuable enough to be utilised for agriculture. For more information on what is meant by moderate and poor quality soil please see the extract from BioAgriNomics VSA in Appendix 1.

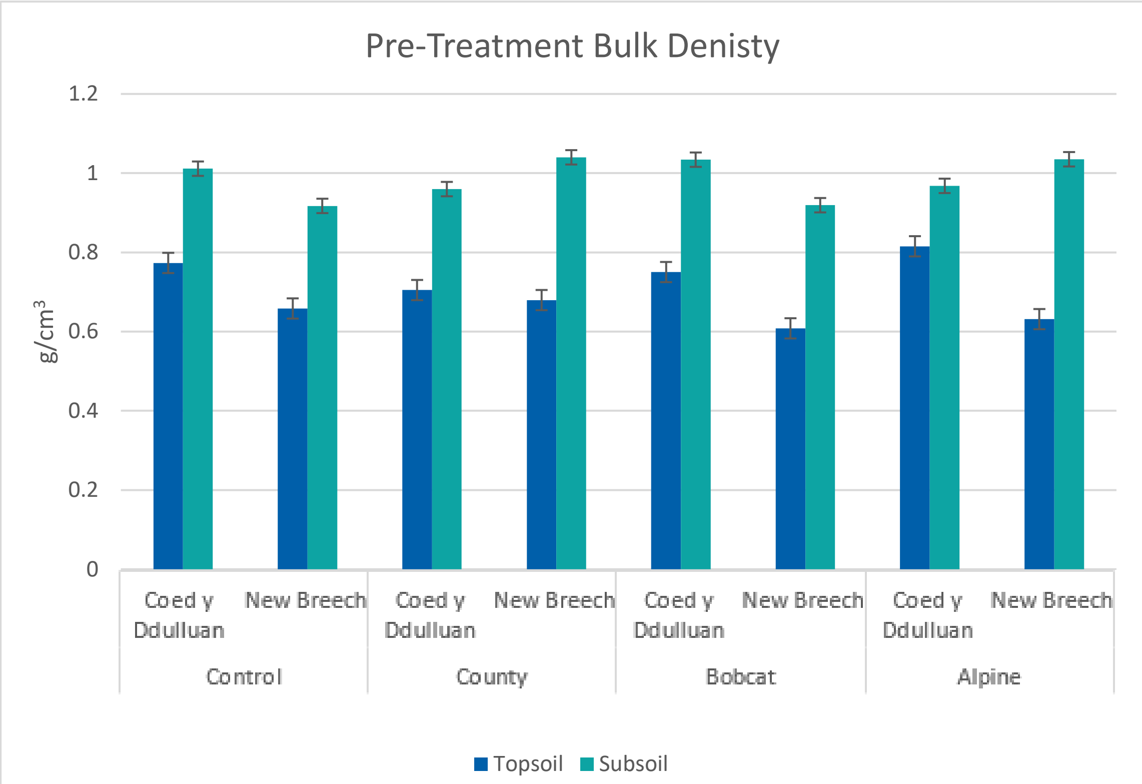

Figure 10 Pre-treatment soil bulk density levels

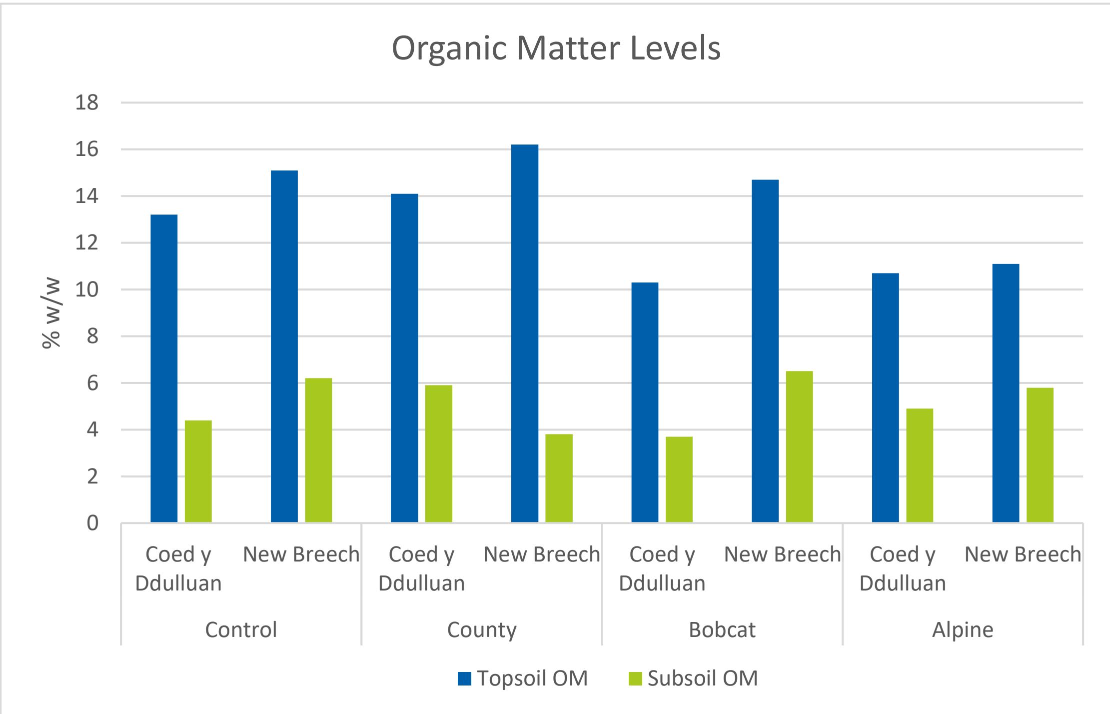

Figure 11 Pre-treatment organic matter level

2 METHODOLOGY

2.1 Experimental Design

At each of the two sites chosen for study, four different treatments were imposed, each with a minimum run length of 20 m x 3 m (see Figure 12). The runs were staked out up the slope and once the ground had reached field capacity the treatments were imposed as this is when maximum compaction generally occurs (Akram and Kemper, 1979). Within each treatment a similar number of machinery passes was required to allow for a fair comparison. After consultation it was agreed that 4 passes by the machinery would constitute a treatment for the purposes of this project. Prior to and post-treatment all runs excluded any vehicle traffic due to the effect this may have had on results and effective catchment runoff, and also because of the Health and Safety issues machinery traffic would pose. Post-treatment surface runoff was collected in a gutter-systems which was inserted at the downslope section of each track to capture surface runoff during different events.

The treatments are as follows:

- Treatment 1: Control treatment (no farm traffic operations)
- Treatment 2: Conventional farm traffic operations (County tractor). See Figures 13 and 14.
- Treatment 3: Farm traffic operations using low impact machinery (Alpine tractor). See Figures 15 and 16.
- Treatment 4: Farm traffic operations using low impact machinery (innovative tracked vehicle - Bobcat). See Figures 17 and 18.

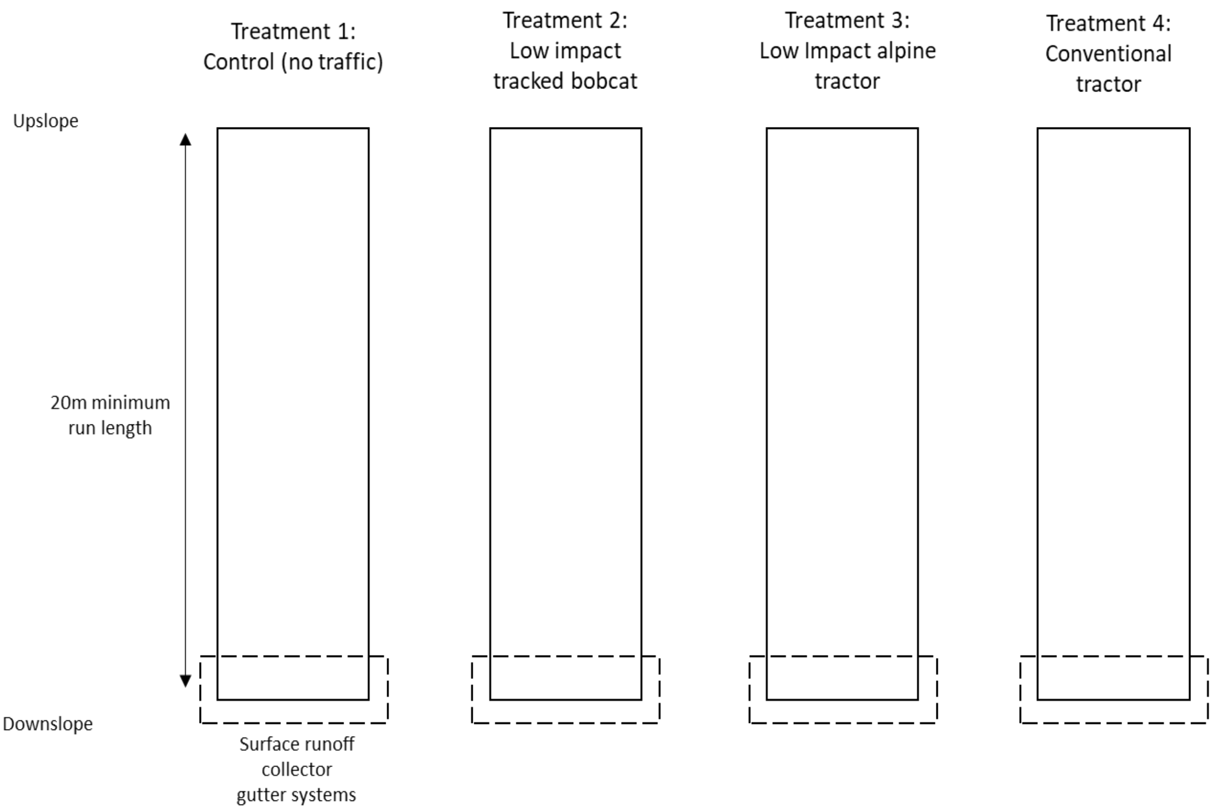

Figure 12 Experimental design diagram

Figure 13 County tractor in action

Figure 14 County tractor in action

Figure 15 Stationary Alpine tractor

Figure 16 Stationary Alpine tractor

Figure 17 Bobcat machine in action

Figure 18 Stationary Bobcat machine

2.1.1 Baseline Studies

Before any of the treatments could be imposed baseline information was collected from the four study areas in both woodland sites. The results of which are described in the introduction section of this report. All surveys are listed and described in Table 1 below.

Table 1 Baseline surveys undertaken before treatments were imposed

Baseline survey	Method of data collection	Method of analysis
Topsoil and subsoil texture	One sample was taken from the subsoil and topsoil from each treatment area in both woods	Lab analysis
Stone Content	The stone content was sampled at 3 points (top, middle and bottom of slope) in each treatment area	Lab analysis
Organic matter	A subsoil and topsoil sample were taken from each treatment area (same sample as texture)	Lab analysis
Bulk density	At both sites BD was sampled at 3 points (top, middle and bottom of slope) in each treatment area. The BD of the topsoil and subsoil were taken at each of the three points	Lab analysis
Compaction	Resistance to penetration was analysed using a penetrometer, 5 readings were taken from each treatment area, location on slope unknown (see Figure 19)	Field assessment
Visual assessment of soil structure	The BioAgriNomics VSA was used to assess topsoil and the VESS was used for subsoil	Field assessment

Figure 19 Measuring for compaction using a penetrometer

2.1.2 Runoff and Erosion Monitoring

Prior to treatments monitoring equipment was installed to ensure the first runoff was captured during the first rainfall event. The equipment was installed at the base of all slopes. Equipment comprised of 3 m lengths of guttering embedded at the soil surface to capture downslope runoff (see Figure 20). The guttering was then connected to piping which channels the collected runoff to 500 L fibre glass storage tanks. Flow-proportional sample splitters were used to collect a representative portion of the runoff based on area monitored and anticipated runoff volumes if runoff volumes are likely to exceed 500 L over a collection period.

Runoff volumes were monitored and sampled at a frequency determined by prevailing weather conditions over the winter period (November - March) 2018-2019. Eight events were sampled at each monitoring site. Field visits to check equipment and undertake routine monitoring were required and close surveillance of local site-specific weather and soil conditions was undertaken. This was achieved by; dialogue with owner/contractor, an onsite rain gauge and an Irriguide water balance model (uses data from the Met Office to interpolate rainfall and estimate soil moisture deficit).

Runoff volumes were thoroughly mixed and then representative subsamples of runoff from each storage tank (see Figure 21) was collected and sent for lab analysis. Runoff was analysed for concentrations of:

- Total Suspended Solids (TSS)
- Total Organic Carbon (TOC)
- Total Nitrogen (TN)
- Total Phosphorus (TP)

Figure 20 Guttering embedded at the soil surface to capture downslope runoff

Figure 21 Surface water storage tanks

2.1.3 Post-treatment Soil Structure Survey

At the end of the monitoring period a detailed soil structure survey was carried out to assess the structural condition of the soils under each treatment (see Table 2). The assessments were complimented with visual evidence of any differences e.g. developments of ruts or rills, compacted soil or deposition fans.

Table 2 Post-treatment soil structure surveys undertaken

Survey	Method of data collection	Method of analysis
Bulk Density	At both sites BD was sampled at 3 points (top, middle and bottom of slope) in each treatment area, the BD of the topsoil and subsoil were taken at each of the three points	Lab analysis
Compaction	Resistance to penetration will be analysed using a penetrometer, 5 readings will be taken from each treatment area	Field assessment
Visual assessment of soil structure	The BioAgriNomics VSA was used to assess topsoil and the VESS was used for subsoil	Field assessment

3 RESULTS

3.1 Runoff and Erosion Results

3.1.1 Runoff Volume

At both sites' runoff volumes increased with rainfall as expected but each of the treatments responded differently in the two woodlands. This can be seen when observing the slopes portrayed on the graphs below. The maximum slope in Coed y Ddulluan was 0.0564 and the maximum in New Breach was 0.2211, thus for every mm of rain of there will be a higher volume of runoff in New Breach than Coed y Ddulluan, despite both sites receiving around the same amount of rainfall. In Coed y Ddulluan runoff levels were no higher than 35 litres whereas runoff volumes reached > 900 litres in New Breach.

In Coed y Ddulluan the County treatment has the largest Y slope and runoff volume and the treatment area which was subject to the Bobcat has the lowest runoff volumes. Whilst the Control and Alpine treatments showed a similar increase in runoff volume over time (see Figure 22).

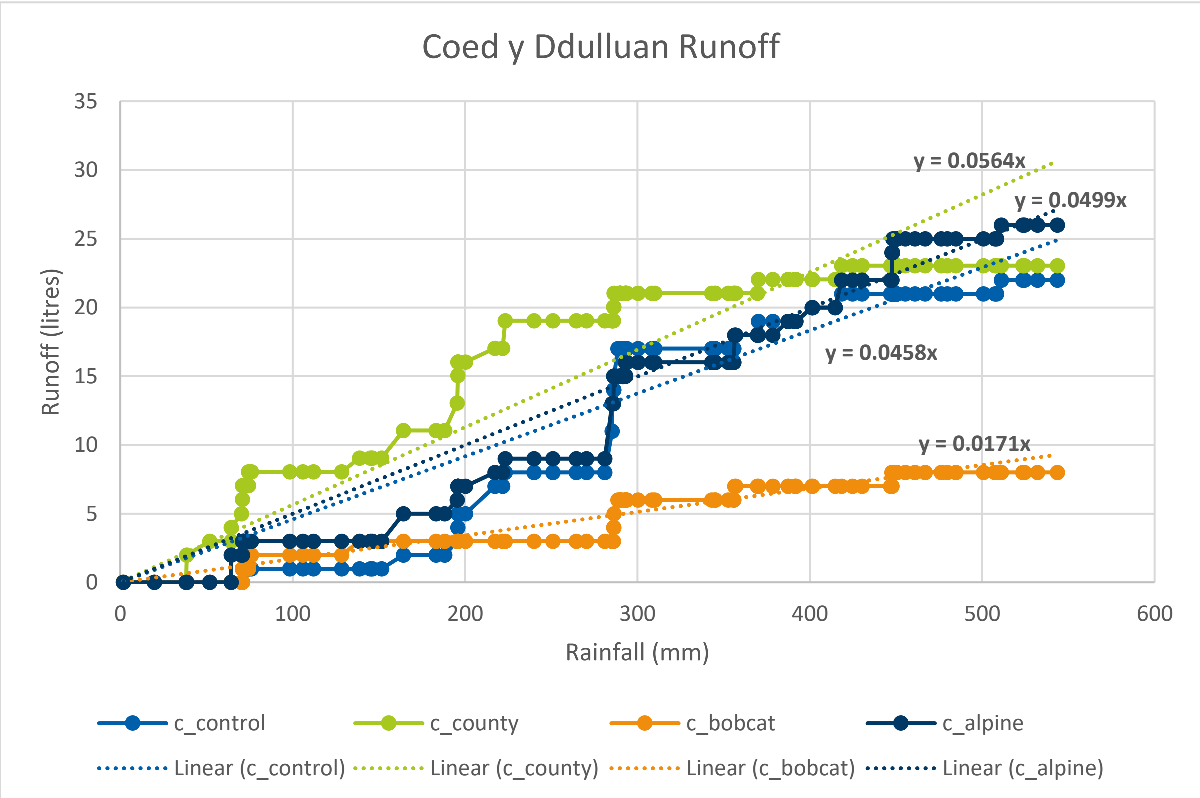

Figure 22 Coed y Ddulluan runoff volume

The Bobcat treatment in New Breach woodland had the opposite effect to that of Coed y Ddulluan, being the treatment with the highest rainfall by far and reaching nearly 1000 litres of runoff. When the outliers are removed from the Bobcat treatment the results can be interpreted more easily. Figure 23 shows runoff volumes after the Bobcat outliers have been removed. Whilst runoff volumes overall are still higher than Coed y Ddulluan they are considerably lower without the outliers (< 120 litres). In this woodland the Alpine treatment has the highest level of runoff followed by the Control.

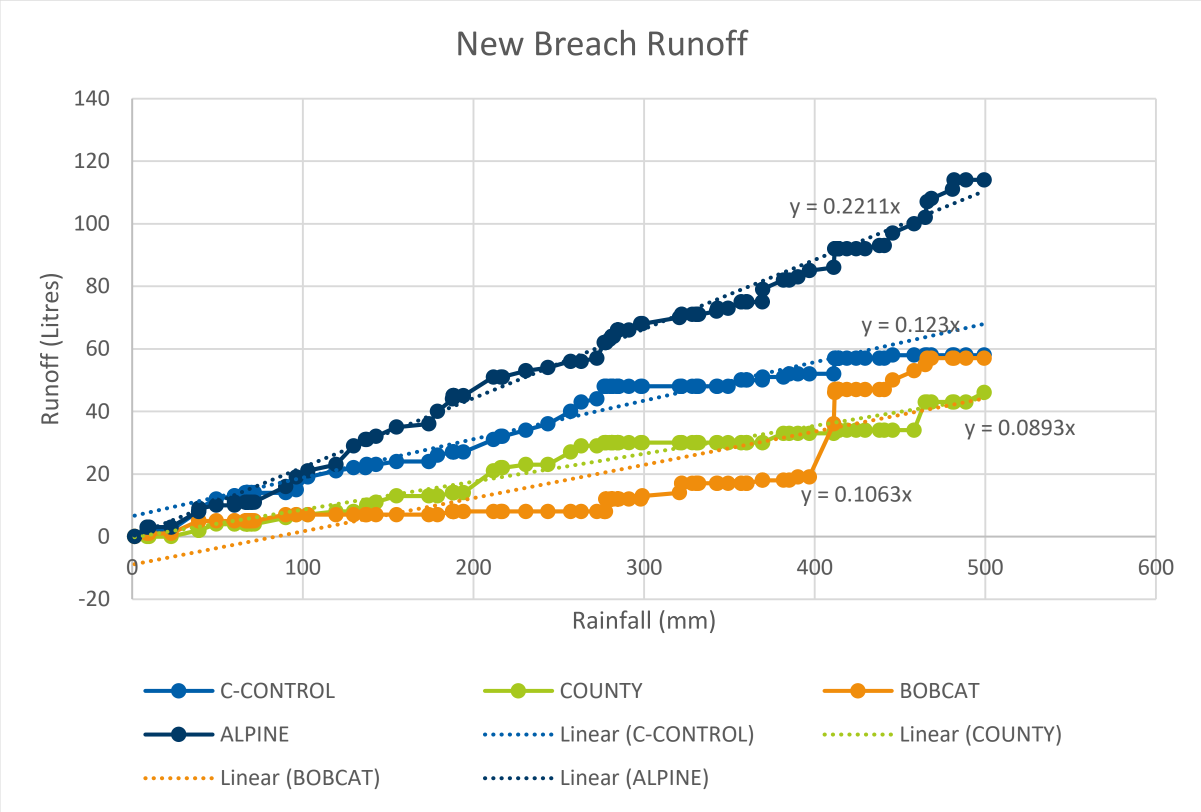

Figure 23 New Breach runoff without Bobcat outliers

3.1.2 Runoff Concentrations

Using the results from the laboratory analysis of samples obtained after each weather event, the weighted average concentration for TOC, TSS, TN and TP in runoff were calculated for each nutrient in each treatment plot. Please see Tables 3 and 4 for weighted average concentrations in mg/l. Results revealed that in both woodlands and across all treatments runoff had higher concentrations of TSS than any other nutrient. TSS concentrations were particularly high from runoff in the Control treatment in New Breach (16.01 mg/l). TSS concentrations obtained from Coed y Ddulluan treatments were much higher in comparison to those obtained from New Breach, ranging from 28.39 mg/l - 58.45 mg/l.

In both woodlands TP concentrations in runoff were lower in all treatments in comparison to all other nutrients. In New Breach the Alpine treatment produced the highest concentrations of TOC, TN and TP, however the Control treatment produced the highest concentration of TSS. The runoff from the Bobcat treatment produced the lowest average weighted concentrations of all nutrients, however in Coed y Ddulluan the runoff from the Control treatment had the lowest nutrient concentrations and the highest concentrations were obtained from the Bobcat treatment with the exception of TCC concentrations (please see Figures 24 and 25).

Table 3 Runoff weighted average concentrations of nutrients in mg/l, for New Breach Wood

Treatment	TOC (mg/l)	TSS (mg/l)	TN (mg/l)	TP (mg/l)
Control	0.63	16.01	0.26	0.05
County	0.17	2.12	0.04	0.01
Alpine	0.70	5.58	0.35	0.08
Bobcat	0.05	0.64	0.01	0.004

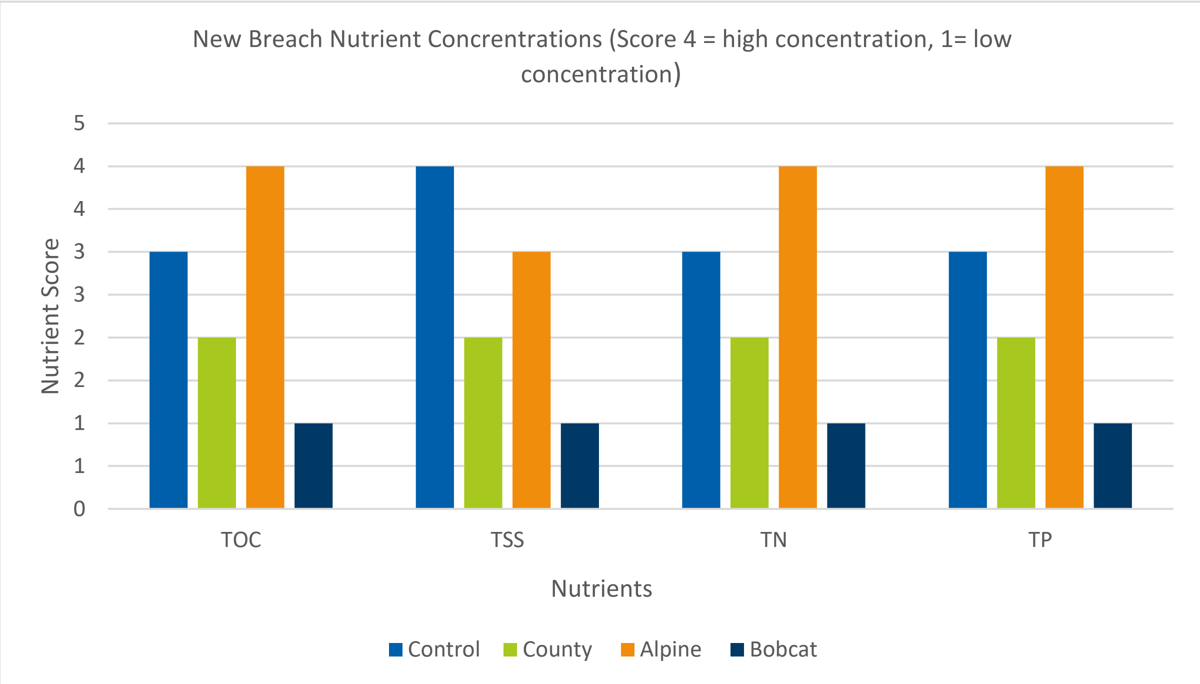

Figure 24 Runoff weighted average concentrations at New Breach

Table 4 Runoff weighted average concentrations of nutrients in mg/l, for Coed Y Ddulluan Wood

Treatment	TOC	TSS	TN	TP
Control	0.88	28.39	0.38	0.09
County	4.46	45.16	1.10	0.21
Alpine	3.70	38.86	0.87	0.17
Bobcat	3.63	58.45	1.28	0.33

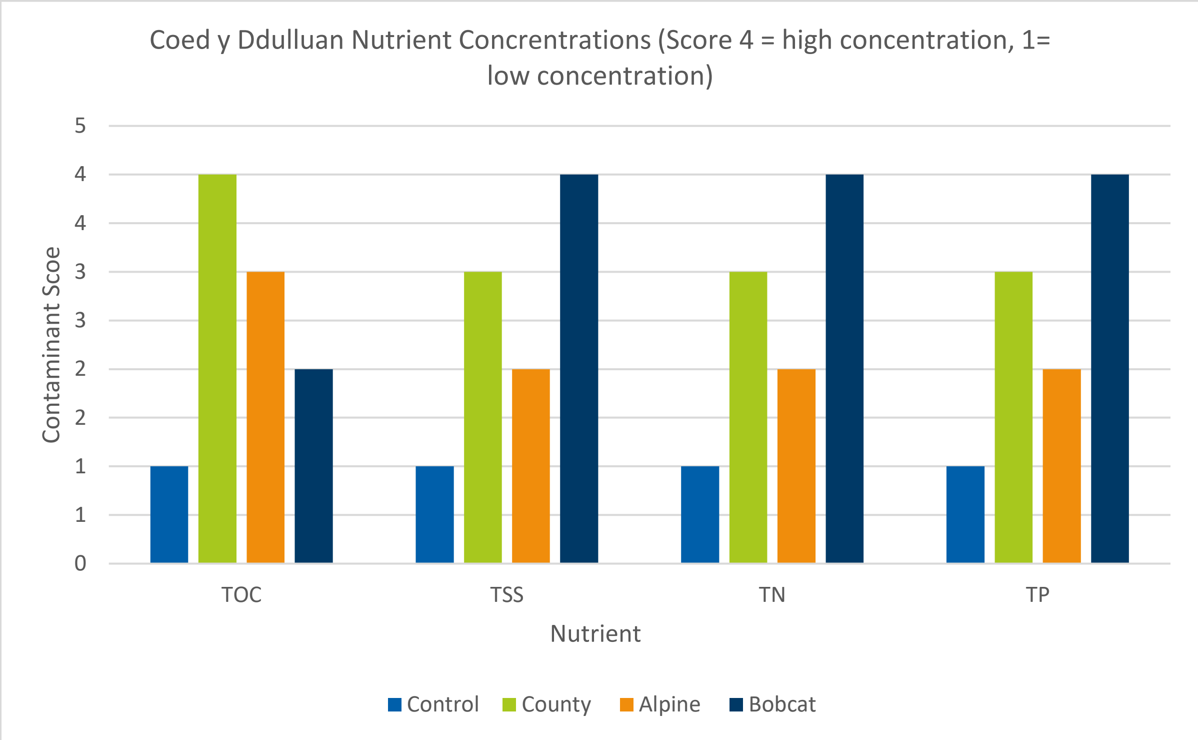

Figure 25 Runoff weighted average concentrations at Coed y Ddulluan

3.2 Soil Structure Results

3.2.1 Visual

The percentage of topsoil in both woodlands categorised as 'poor' increased and subsoil categorized as poor decreased in both. However, in Coed y Ddulluan subsoils could not be reached in three of the soil pits (see Tables 5 and 6). None of the soil pits improved above moderate quality. There was also evidence of rutting, which is one of the first visible signs of damage from vehicle traffic when soil is in a compactable state (Startsev and McNabb, 2000). The most noticeable rutting appears in the County treatments (in both woodlands). There is also evidence of machinery passes in the Bobcat, Alpine and conventional treatments, to a lesser extent. Please see Table 7 for images of ruts made by machinery.

Table 5 Visual soil assessment in New Breach

New Breach	Pre-treatment score	Post-treatment score
Topsoil	8% categorized as poor	66% categorized as poor
Subsoil	92% categorized as poor	75% categorized as poor and the remainder could not be reached to assess

Table 6 Visual soil assessment in Coed y dulluan

Coed y Ddulluan	Pre-treatment score	Post-treatment score
Topsoil	25% given a score of poor	33% given a score of poor
Subsoil	100% categorized as poor	75% categorized as poor

Table 7 Visual evidence of soil damage in treatments

New Breach – Bobcat 	New Breach - County 	New Breach – Alpine 	New Breach – Control 
Coed y Ddulluan - Bobcat 	Coed y Ddulluan – County 	Coed y Ddulluan – Alpine 	Coed y Ddulluan - Control 

3.2.2 Compaction

Post-treatment soil resistance to penetration was taken using a penetrometer (see Figure 26 for results obtained from the two woodlands). In Coed y Ddulluann only the County treatment had a higher level of compaction in comparison to the Control ride (County resistance to penetration result was 108% of the Control result). However in New Breach Wood all treatments showed higher levels of compaction across all treatments when compared with the Control treatment, most noticeably in the County treatment (compaction is 130% of the Control treatment ride) (see Tables 8 and 9). The sampling strategy undertaken for this study does not allow for the comparison of penetrometer results obtained pre-treatment and post treatment, due to large differences in soil moisture contents.

Table 8 Resistance to penetration results obtained from each treatment ride in Coed y Ddulluan

Treatments in Coed y Ddulluan	Control	Bobcat	Alpine	County
Resistance to penetration (MPa)	139	126	128	150
Penetrometer result as a % of the Control treatment		91%	92%	108%

Table 9 Resistance to penetration results obtained from each treatment ride in New Breach

Treatments in New Breach	Control	Bobcat	Alpine	County
Resistance to penetration (MPa)	70	78	83	91
Penetrometer result as a % of the Control treatment		111%	119%	130%

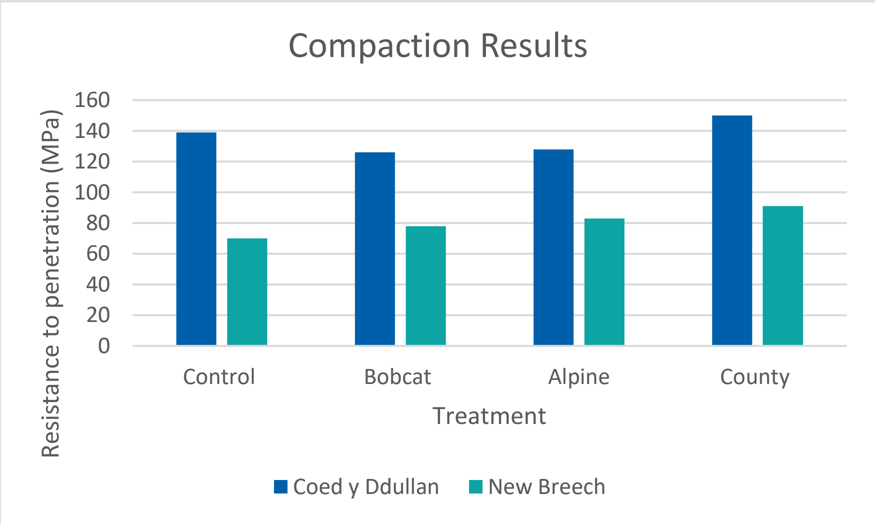

Figure 26 Compaction results obtained from a penetrometer used in all treatment rides in Coed y Ddulluan and New Breach Wood

3.2.3 Bulk Density

Topsoil BD readings appears to have decreased post-treatment across all rides, bar the Bobcat treatment in New Breach in which it has marginally increased. Results suggest that soil has become less compact after the treatments have been undertaken (see Figure 27). Subsoil BD results show no obvious pattern, however more of the BD results appear to have declined than increased (see Figure 28).

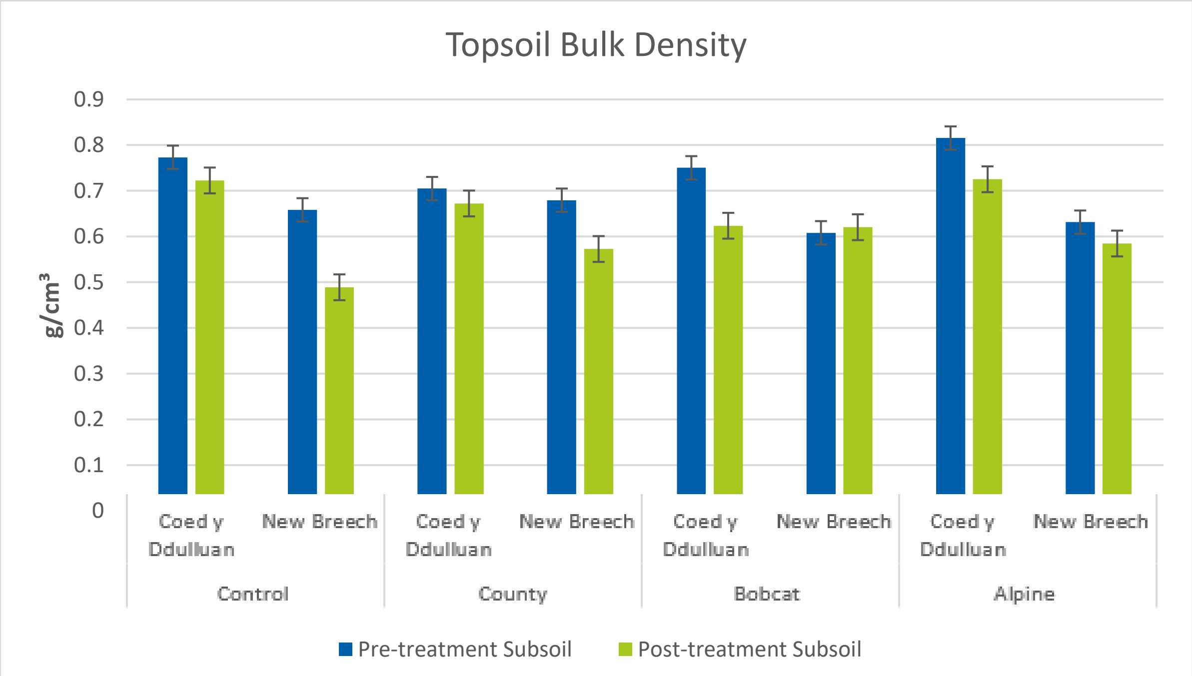

Figure 27 Post-treatment topsoil bulk density results

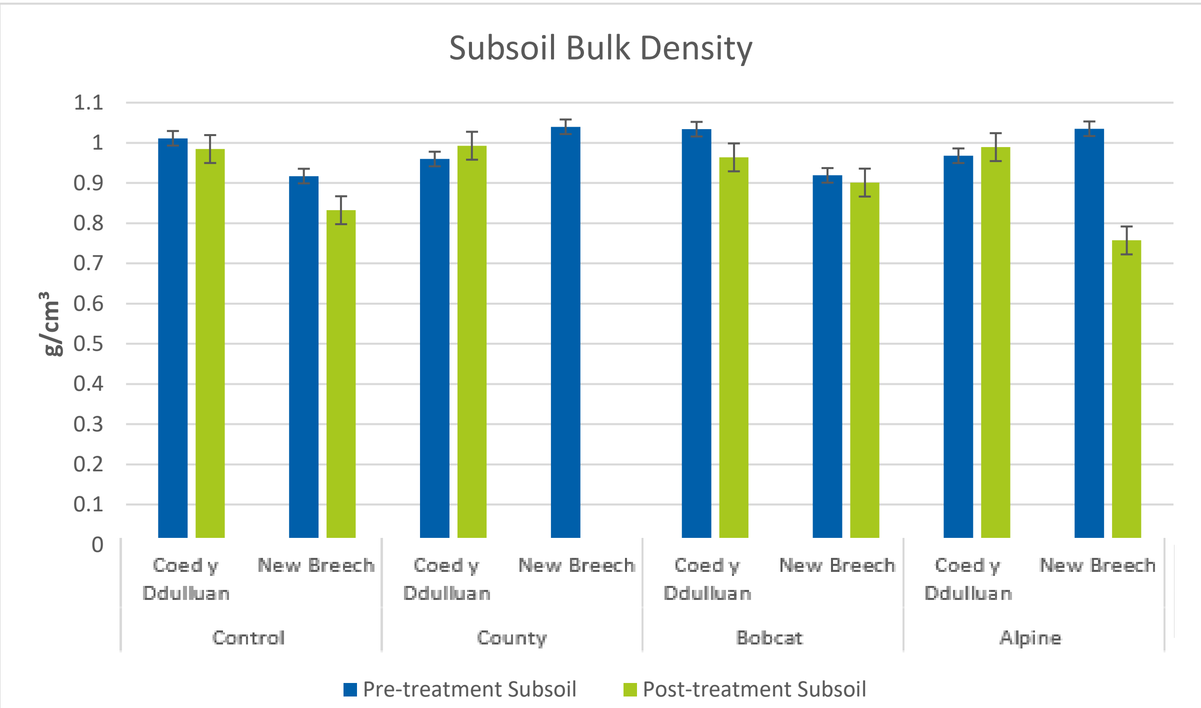

Figure 28 Post-treatment subsoil bulk density results

4 DISCUSSION

It was hypothesised that conventional machinery (County treatment) would have the largest negative implication on soil function and water quality. It was expected that BD and compaction would increase mostly severely in the County treatment and runoff volumes and nutrient concentrations would be highest for this treatment across both woodlands. Compaction is a likely outcome of machinery passes as the site soil is clay based, thus more vulnerable to soil compaction than coarse-textured soils (sand, sandy loam, loamy sand) (Armpooter, 2011). Some impact on soil and water may be expected from the low pressure machinery (Alpine and Bobcat) but not to the extent of the County treatment. It is unlikely that there will be differences in the Control treatment results.

In light of the results the null hypothesis must be accepted. In New Breach the highest nutrient concentrations found in run-off volumes (for 3 of the 4 nutrients analysed in the laboratories) were obtained from the Alpine treatment and from the Bobcat treatment in Coed y Ddulluan. In New Breach the Bobcat treatment produced the largest volume of runoff, exuding extreme volumes compared with other treatments, reaching > 900 litres. Whereas all other treatments in this woodland had runoff volumes < 150 litres. The runoff data generated from the Bobcat treatment could be due to a few extreme runoff events, uncharacteristic of the rest of the monitoring period. Once outliers were removed from the data the Alpine treatment produced the largest runoff volume and the Bobcat appeared to have a runoff volume similar to other treatments. Though, even without the extreme events overall runoff from New Breach was still much higher than in Coed y Ddulluan, despite having received the same amount of rainfall. The unusually high volumes of runoff from the Bobcat treatment may have been due to natural drainage patterns and another source of runoff from the field at the top of woodland (see Figures 29 and 30). Although, prior to this study there was no background data available on the hydrology of treatment rides. The usual runoff volume from treatment rides and which ride is naturally wetter is unknown. The lack of information on pre-treatment runoff volumes is a recognised limitation of the project, thus it cannot be assumed that treatments imposed caused the runoff results.

The lower levels of runoff of generated from Coed y Ddulluan may have potentially been down to topographical variables. A valley lay approximately 50 m from Coed y Dddulluan, which may have been responsible for diverting a lot of surface run off away from the treatments. Higher volumes of runoff in New Breach conversely may have been due to natural drainage funnelling surface water into treatments. The Control was expected to yield the lowest runoff levels as no treatments were imposed in this area, however this was not the case in either woodland. The natural channel which formed in this treatment area could have caused the unexpected results in this ride.

Treatment types in New Breach did not appear to have any relationship with nutrient concentrations in the runoff samples collected. Though in both woodlands TSS concentrations were much higher than the other nutrients analysed.

Post-treatment BD was expected to increase due to compaction, particularly in the County ride. Especially as the site soil (clay based) was assumed to be more vulnerable to soil compaction than coarse-textured soils (sand, sandy loam, loamy sand) (Armpooter, 2011). In previous research clay soils have shown the highest BD and the lowest porosities after being subject to machine traffic (Gomez *et al.,* 2002; Smith, 2003). This was not the case for this investigation. When BDs exceed 1300 kg m^{-3} (1.3g/cm^3) in forest soils they are considered compact, especially in cases of medium- to fine-textured soils. In this case BD levels would not be considered compact as they did not exceed 0.99g/cm^3 post treatment. They were in fact closer to the compaction threshold pre-treatment (Armporter, 2011). When resistance to penetration results from treatment rides were compared with the Control treatment the County results were higher than the Control in both woodlands, however only in New Breach did the Bobcat and Alpine treatments have a slightly higher level of compaction than the Control treatment.

Figure 29 Runoff channel in Control treatment

Figure 30 Runoff from field above New Breach

Large increases in compaction readings may not have increased post-treatment because the slope of the sites chosen for this experiment were not steep enough. Previous research has found that soil disturbance in extent and depth increased with slope. Forest Research classifies the gradients of Coed y Ddulluan and New Breach as *level* to *gentle* (see Appendix 2 for the Forestry Commission classification of terrain). Slopes between 10-15% may not be steep enough to cause a serious level of compaction. Although other studies found that slopes between 10-20% which endure three passes can cause decreases of 15%, 22%, and 67% in total porosity, water content and forest floor mass, respectively (Solgi and Najafi, 2014). Further research is needed to assess whether slope has an impact on the level of soil compaction caused by forest machinery.

Water and soil issues may not have been caused by the machinery in this experiment because the ground conditions were not poor enough to warrant low impact machinery. Tracked machinery such as the Bobcat should be employed where the ground has a low load bearing capacity e.g. on peaty gleys in drier areas; soft mineral soils in wetter areas; peaty gleys in wetter areas and on deep peats. Whilst the site may have been wetter than other parts of the UK the soil may not have been in a condition that warrants low pressure machinery.

It has also been identified that comparative to agricultural soils, forest soils have a much higher spatial variability due to the influence of stem flow, tree crown and root architecture. Windthrow, woodland animals and wildfire can also cause unevenness in soil. The notorious variability requires particular attention to soil sampling design, and number of samples to be taken to express a mean tendency accurately. Thus, if readings were not taken in the same location pre and post-treatment the spatial variability of woodland soil could impact the reliability of BD results and explain why compaction appeared to be higher pre-treatment (Moffat, 2003).

Although BD can be a useful measure of soil compaction caused by poor management choices it has been disputed whether BD results are completely accurate (Moffat, 2003). Ampoorter (2011) also found that BD and penetration resistance, has lower degrees of compaction after treatments were imposed on forest soils, even on the vulnerable soil textures. The results of Ampoorters thesis indicated that quantification of the soil impact based on BD and penetration resistance may lead to an underestimation of impacts inflicted on soil. Instead more sensitive soil variables such as soil carbon dioxide concentration should be taken into account. An increase of soil carbon dioxide (CO^2) concentration and decrease of oxygen (O^2) concentration can be caused by an unfavourable influence on soil aeration. Surface rutting on the other hand is classed as an invaluable indicator of soil damage by poor husbandry (Moffat, 2003).

Alternatively, BDs may have been lower post-treatment as the second results may have been taken too long after the treatments took place. Natural processes can cause soil compaction to disappear over time, the seven-month period between BD sampling may have been sufficient to reverse any damage done by the small machinery used during this investigation (Armpooter, 2011). If they had been taken as soon as the treatments had been imposed they may have shown different results.

Although results did not show distinctive differences between treatments they did demonstrate that the low impact machinery was able to successfully gain access to small woodlands, which are currently undermanaged. The low impact machinery was just as successful as the conventional machinery at clearing a woodland ride and none of the treatments caused compaction. Or at least if compaction has occurred soil had returned to low levels of compaction seven months after machinery had passed over the soil. Further research could entail conducting a feasibility study on the low impact machinery accessible to woodland owners or a similar study could take place with more sensitive indicators of soil quality than bulk density and penetration resistance.

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6 APPENDICES

Appendix 1 BioAgriNomics VSA soil condition descriptions

GOOD CONDITION VS = 2
Soil dominated by friable, fine aggregates with no significant clodding. Aggregates are generally subrounded (nutty) and often quite porous.

MODERATE CONDITION VS = 1
Soil contains significant proportions (50%) of both coarse clods and friable fine aggregates. The coarse clods are firm, subangular or angular in shape and have few or no pores.

POOR CONDITION VS = 0
Soil dominated by coarse clods with very few finer aggregates. The coarse clods are very firm, angular or subangular in shape and have very few or no pores.

Appendix 2 Classification used by the forestry commission to assess terrain

Class				
1	**2**	**3**	**4**	**5**
• Ground Condition				
Very Good	Good	Average	Poor	Very Poor
Dry sands and gravels	Firm mineral soils	Soft mineral or ironpan soils in drier areas	Peaty gleys in drier areas; soft mineral soils in wetter areas	Peaty gleys in wetter areas; deep peats
• Ground Roughness				
Very even	Slightly even	Uneven	Rough	Very Rough
Obstacles (boulders, plough furrows etc) small or widely spaced	Intermediate	Obstacles of 40cm at 1.5 - 5m spacing	Intermediate	Obstacles of 60 cm or more at 1.5 - 5m spacing
• Slope				
Level	Gentle	Moderate	Steep	Very Steep
0–10% 0.6º	10–20% 6–11º	2 –33% 11–18º	33–50% 18–27º	50%+ 27º+